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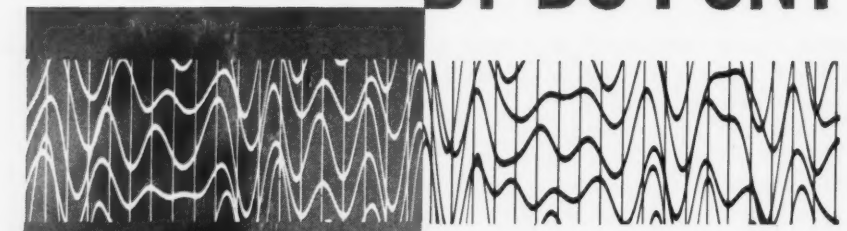

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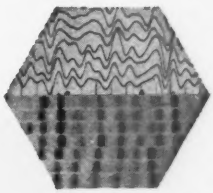

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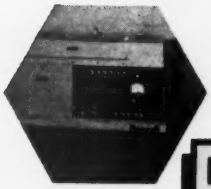

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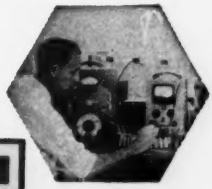

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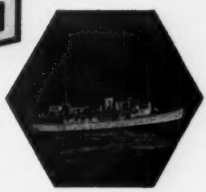

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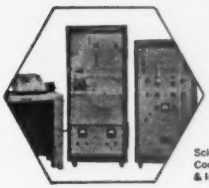

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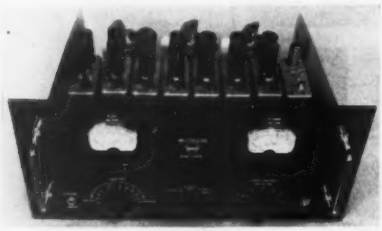

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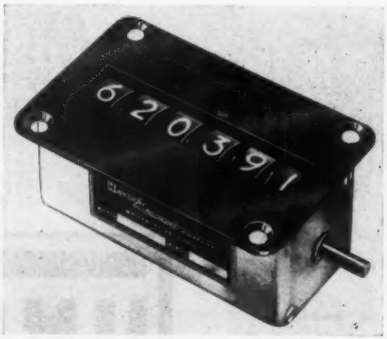

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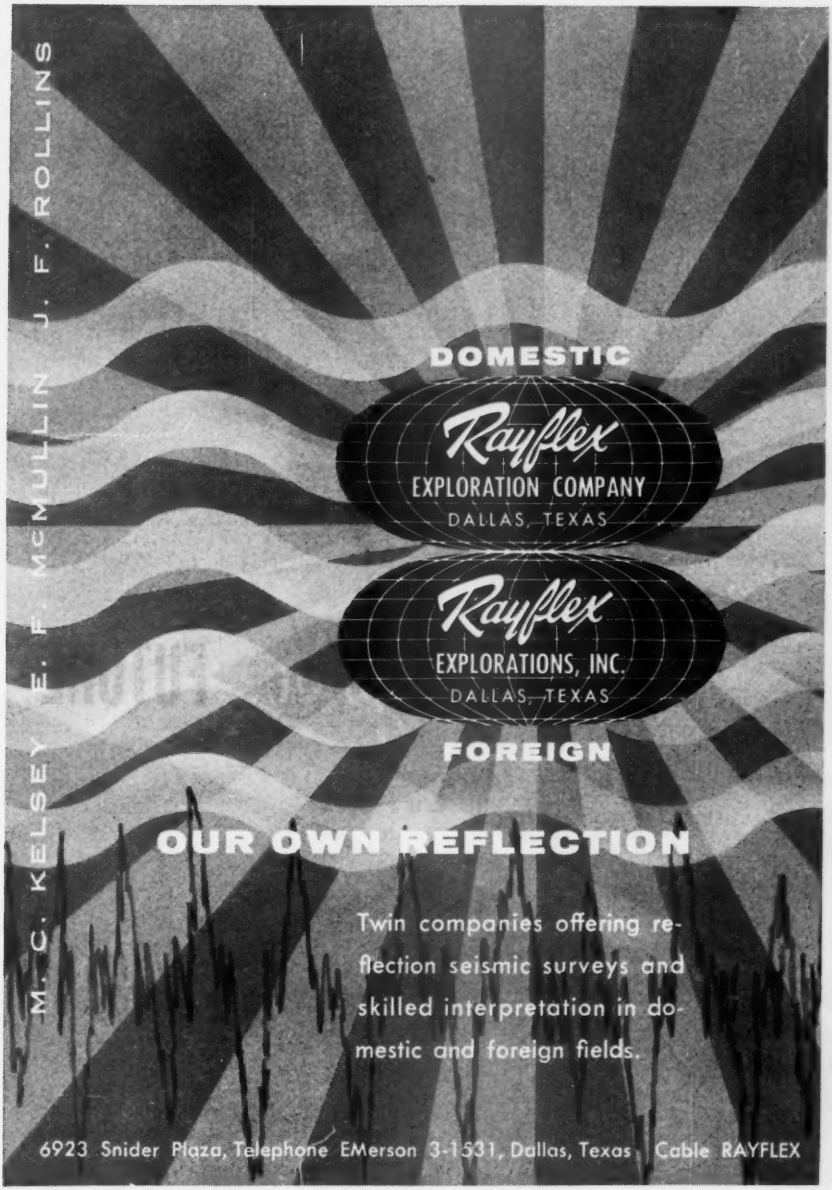
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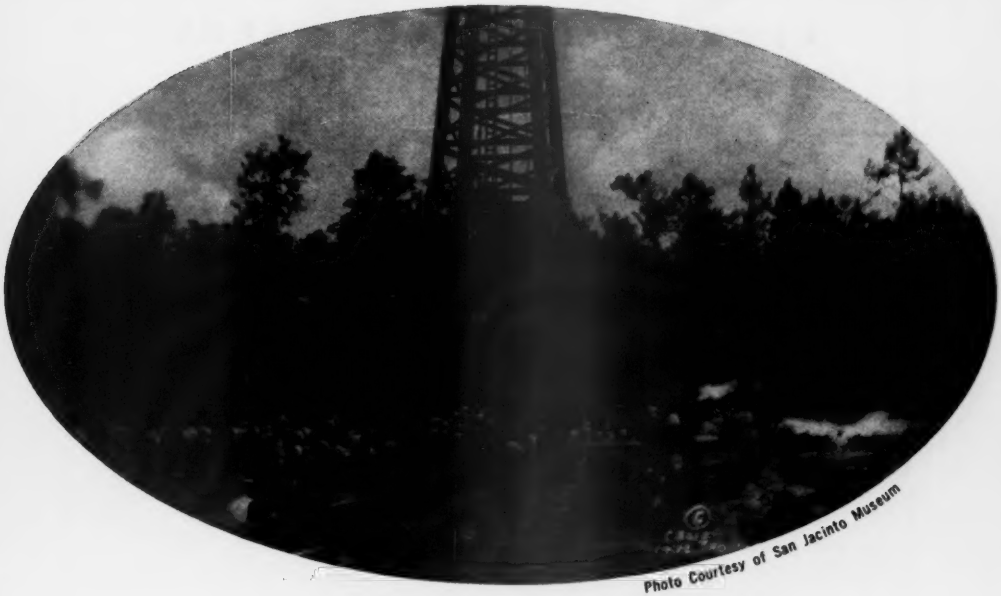

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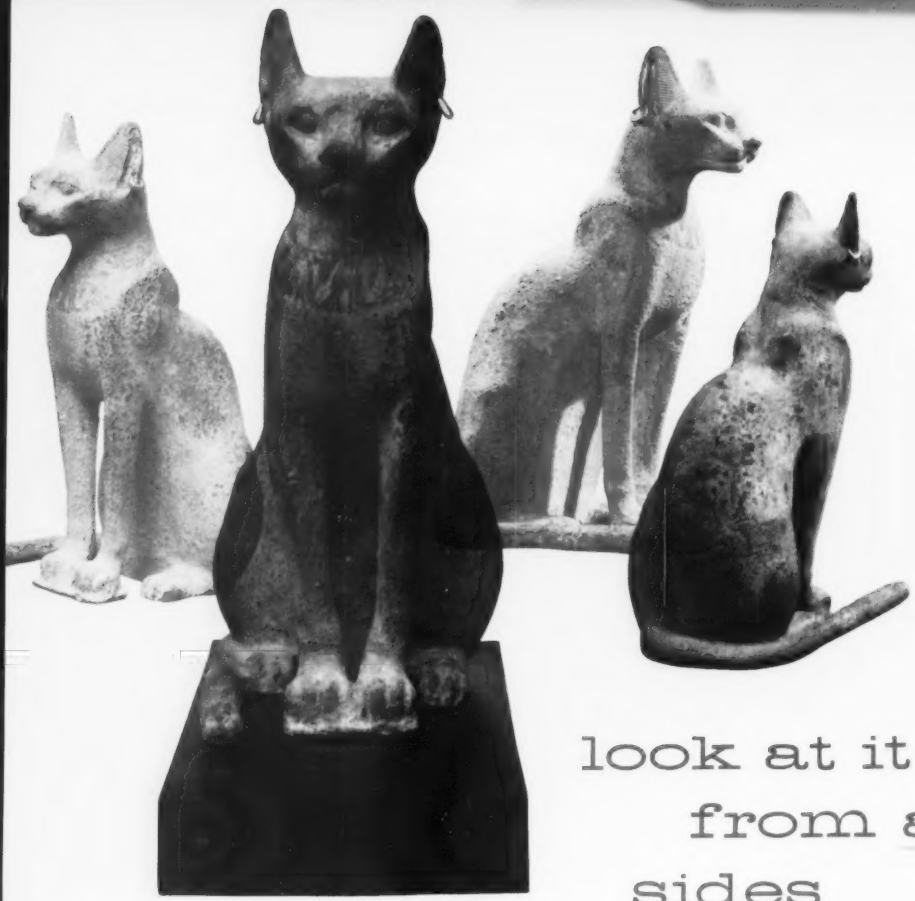

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GEOPHYSICS

SEISMIC REFLECTIONS FROM LAYERING WITHIN THE PRE-CAMBRIAN BASEMENT COMPLEX, OKLAHOMA*

M. B. WIDESS† AND G. L. TAYLOR†

ABSTRACT

Reflections from within the pre-Cambrian basement complex were recorded in the vicinity of the Wichita Mountains in southwestern Oklahoma. The reflections, of good quality and persistence, depict a section in excess of 20,000 ft of igneous rocks that appears like a seismic section of sedimentary formations.

A well in the area drilled 4,000 ft of this pre-Cambrian section, encountering alternating layers of silicic and gabbroic igneous rocks exhibiting high contrast in density. Pre-Cambrian outcrops of much of the Wichita Mountains, comprising comparable types of rocks, display sheet-like, gently dipping layers, some of which persist for several miles. The seismic reflections are thus produced by the igneous layers of differential acoustic properties. An abrupt change of direction of dip occurring at about mid-depth of the seismic section precludes the possibility that the seismic events are multiple reflections.

INTRODUCTION

There is nothing unusual about observing coherent and regular reflections on seismic records that arrive beyond the reflection time to the top of the basement complex. The generally accepted interpretation for the late arrivals is that they are multiple reflections from interfaces within the overlying sedimentary section, the cumulative time exceeding the primary reflection time to the basement. The present paper does not disagree with this explanation as the usual rule. The purpose here is to illustrate that there are also exceptions to the rule, that circumstances may be encountered wherein regular seismic events that appear timewise to be reflections from within the basement complex are in actuality just that—*they are* reflections from within the basement complex.

SEISMIC CROSS-SECTION

The area where reflections from interfaces within the basement complex were observed is in the vicinity of the Wichita Mountains in southwestern Oklahoma. The location of the seismic traverse is shown in Figure 1. Shotpoint 1, on the

* Paper read at the 28th Annual International Meeting of the Society at San Antonio on October 14, 1958; at the 11th Annual Midwestern Meeting at Tulsa on April 17, 1958; and before the Fort Worth Geophysical Society, March, 1958. Manuscript received by the Editor December 17, 1958.

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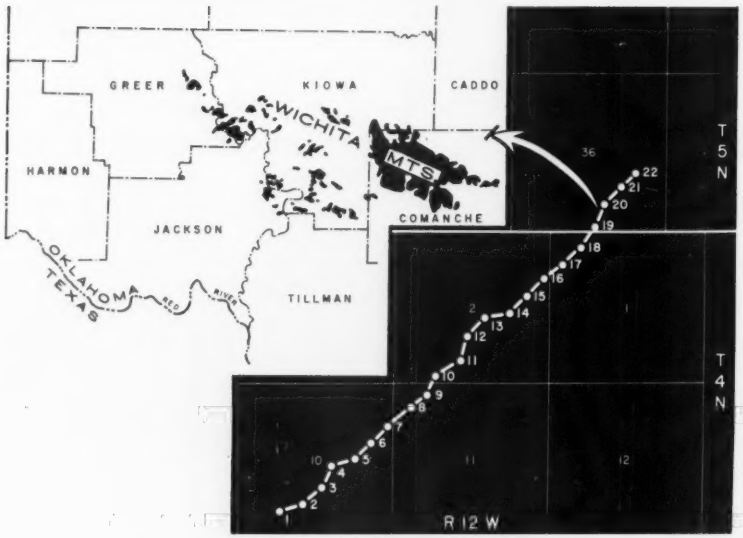


FIG. 1. Location of the seismic traverse, in the vicinity of the Wichita Mountains, southwestern Oklahoma.

southwest terminus of the continuous-profiling line, is about two miles from outcropping pre-Cambrian igneous rocks in the foothills of the Wichita Mountains, a fault of large throw occurring in this interval. The exposed Wichita Mountains proper are approximately four miles beyond the first igneous outcrops. A well, the Pan American No. 1 Perdasofpy, that drilled deep into the basement complex, is offset 2,300 ft southeast from shotpoint 6 on the seismic traverse.

The seismic cross-section along the traverse line is shown in Figure 2. This is a migrated time section, such that the ordinate scale is the vertical component of reflection time, referred to a substantially flat datum level. Shotpoint spacing is about 750 ft. The horizontal scale shows exaggeration by about 50 percent relative to the vertical scale if the vertical dimension is converted to depth using observed and estimated velocity.

The Pan American No. 1 Perdasofpy is shown at its projected position on the cross-section, depth being transcribed to time by using the velocity determined from a survey in that well. (The bend in the well is the drift of the hole along the azimuth of the seismic line.) The well drilled a normal section of Cambro-Ordovician age, comprising Arbuckle limestone and Reagan sand and conglomerate, and encountered the pre-Cambrian basement complex at a depth of 5,630 ft. About 4,000 ft of silicic and gabbroic igneous rocks were then penetrated by the test before it was abandoned at a depth of 9,674 ft.

The striking feature of the seismic cross-section is that it is indistinguishable from ordinary seismic sections of sedimentary formations. Numerous reflections

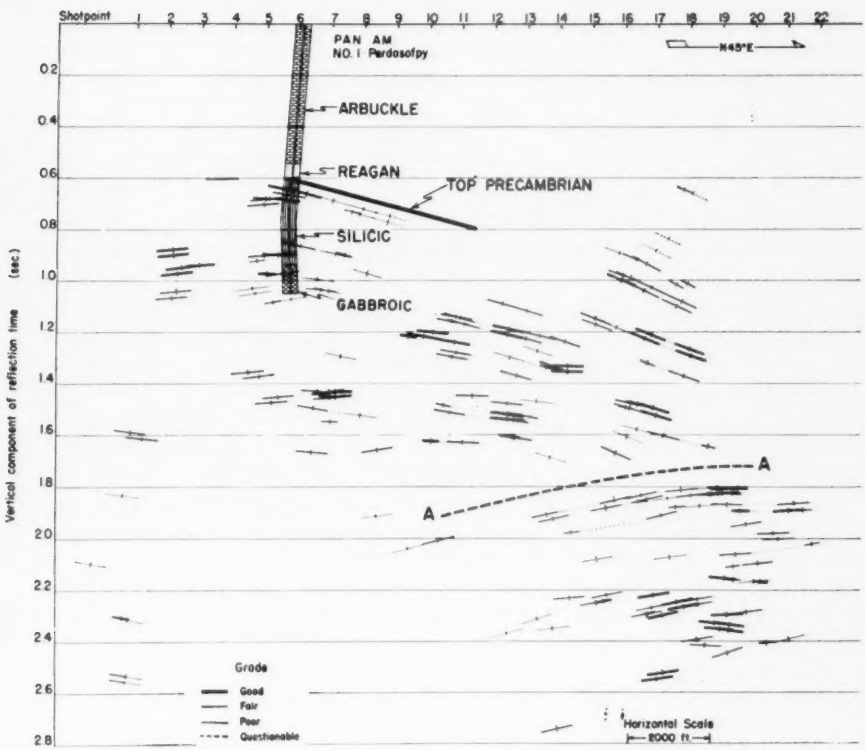


FIG. 2. Seismic cross-section in terms of migrated time. The Pan American No. 1 Perdasofpy is shown in its projected position, and its log is transcribed to time using velocity measured in the well. About 4,000 ft of pre-Cambrian igneous section was penetrated by the well. The line A-A marks an abrupt change of seismic dip that precludes multiple reflections.

persist beyond a single profile and some persist for many profiles. The persistence, however, does not necessarily determine whether these events are multiple reflections or primary reflections. The factor that is crucial to the question is the abrupt change of dip that occurs at the line marked A-A. One notes that almost all dips above this line are northeast, while almost all dips below the line are southwest. There is no set of circumstances plausible to this area that would permit multiple reflections to assume an abrupt change of dip over such a wide sweep of the section. It is concluded, therefore, that the events are primary rather than multiple reflections.*

* The well velocity survey at the Perdasofpy test showed that the average velocity to the top of pre-Cambrian is about 19,000 ft/sec while the interval velocity across the 4,000 ft of pre-Cambrian section is about 18,000 ft/sec. The small contrast in this high velocity discourages normal-moveout analysis to distinguish between primary and multiple reflections.

Profiles in which spreads were oriented at right angle to the present line showed continued coherence of reflections with relatively little dip in that direction, eliminating the possibility that the events are reflected refractions arriving from approximately the cross-direction.

The reflection records from which the cross-section in Figure 2 was prepared are presented in Figure 3. In the left half of the figure a reflection from near the top of pre-Cambrian appears prominently. The good quality and persistence of reflections from within the basement complex are best represented in the right half of the figure. The abrupt change of dip at about 1.8 sec is conspicuous on the latter records.

THE PRE-CAMBRIAN ROCKS

The central part of the Wichita Mountains exposes a belt of pre-Cambrian rocks that is approximately 65 miles long and 20 miles wide. Almost all of this rock is igneous in origin. The unusual feature of the mountains is that the exposed igneous rocks display a sheet-like character. Lacking strong folding, this layering simulates gently folded sedimentary beds. Some of the individual layers of the complex can be traced for several miles. Figure 4 shows the mile-long layer of granophyre on Mount Sheridan that from a distance has all the appearance of a sedimentary cap. Gabbroic rocks are below the ridge.

The pre-Cambrian rocks of the Wichita Mountains consist largely of intrusive and extrusive layers of silicic rocks (granophyres, porphyritic rhyolites, rhyolites) and a lesser amount of gabbroic rocks (diabase, gabbro, basalts), some of which have received detailed description in recent years (Huang, 1955; Hamilton, 1956). Metamorphosed sedimentary rocks, though generally prominent in other pre-Cambrian igneous mountains, are rare in the Wichita Mountains. The present sheet-like character of igneous layers suggests that little deformation took place while the complex was being formed.

The pre-Cambrian rocks encountered in the 4,000 ft of basement complex drilled by the Pan American No. 1 Perdasofpy are similar to the rocks exposed to the south of the Wichita Mountains. Perhaps slightly more extrusive layers of silicic rocks (rhyolites, tuffs, volcanic glass) were present in the test than in a comparable thickness of pre-Cambrian in the Wichita Mountain outcrops. The presence of several sills of gabbroic rock indicates that they are not necessarily the oldest igneous rocks in the pre-Cambrian complex.

It is expected that for a considerable depth below the total depth of the test, the section continues to be layers of intrusive sills and extrusive flows of rocks of silicic and gabbroic composition. There is no geologic reason why these alternating layers of igneous rocks could not extend to depths exceeding 30,000 ft, reflection time interval of more than 3 sec. This is suggested by the large exposed area of igneous rocks in the Wichita Mountains. Thus, the occurrence of sheet-like layers in the pre-Cambrian section, the wide contrast in the type of rocks comprising the different layers, and a probably very thick section of the layered

rock provide all the factors to produce sedimentary-type reflections. Confirmation is therefore provided for the conclusion reached from the seismic data that primary rather than multiple reflections are involved in the observed seismic section.

RELATION OF THE DENSITY LOG TO REFLECTIONS

The 4,000 ft of igneous section drilled by the Perdasofpy well provide an opportunity for direct comparison between seismic reflections and the penetrated igneous layers. Such a comparison is shown in Figure 5. At the bottom of the figure is a log in which the silicic and gabbroic rocks are distinguished, striations for the silicic, hatchures for the gabbroic. Depth is referred to the ground elevation. Rock density determined from the samples is shown above the lithologic log. Density is not the same for all silicic layers or for all gabbroic layers. Varying from 2.5 to 3.0, the density is generally high for the gabbroics and generally low for the silicics.

The corresponding portion of a seismic record obtained by the side of the well in the course of the well velocity survey is shown at the top of the figure. The outstanding reflection on this record, as well as on the 25 other records obtained at the location, is the R-reflection at a time of 0.906 sec (referred to a datum plane at an elevation of 1,300 ft). An examination of the density log shows that if the density alone were to be the criterion for reflective properties, the sill shown matching the R-reflection is the best reflector on the log, because the sill possesses as high a contrast of density as any interface on the log, and particularly because the thickness of the isolated sill closely approximates $\frac{1}{4}$ wave length (about 90 ft), the thickness that provides reinforcement between reflections from the top and bottom interfaces. The not unreasonable reflection time delay of 40 milliseconds (after applying well velocity data but neglecting filter correction) was introduced by shifting the record to match reflection R with the sill as shown.

With this alignment, other events may be compared, bearing in mind also that the depth scale of the log has been matched to the time scale of the record on the basis of a velocity of 18,000 ft/sec, the overall interval velocity determined from the velocity survey for the 4,000 ft of igneous section. Since velocity unquestionably varies within the igneous section, the comparison can be treated only as an approximation. The second best reflection observed on the records as a whole is the S-reflection at a time of 0.955 sec. This reflection is to be matched with the top of the thick gabbroic layer. Though the reflection time is then excessive by about 4 milliseconds, the match may be considered to be reasonably close.

The reasonable fit between the two best reflections and the respective igneous layers lends support to the conclusion that reflections from igneous layers are obtained. Other reflections are not readily matched with the density contrasts, and information on velocity contrasts is required. A continuous velocity survey was in fact run in the well, one of the very first such commercial surveys, but unfortunately the instrument failed to operate satisfactorily.

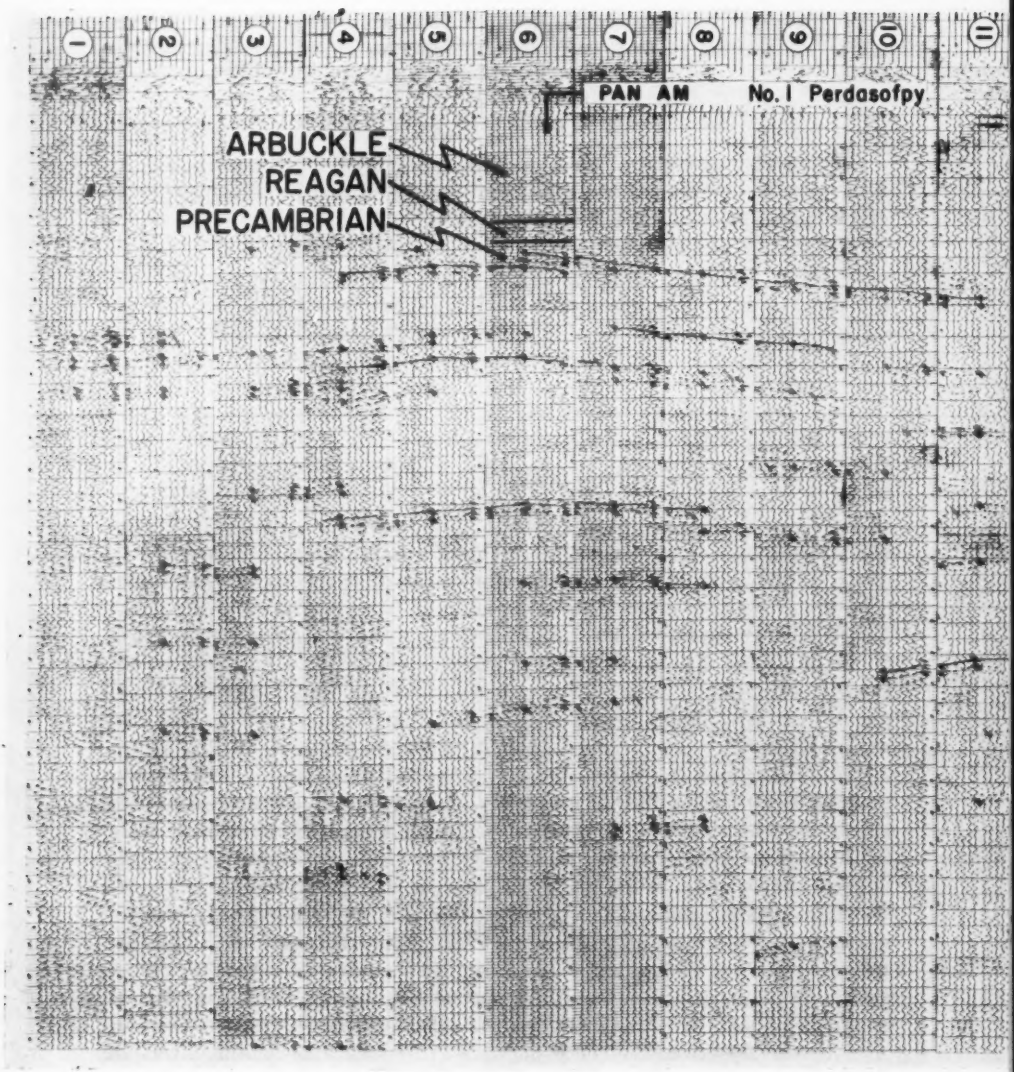
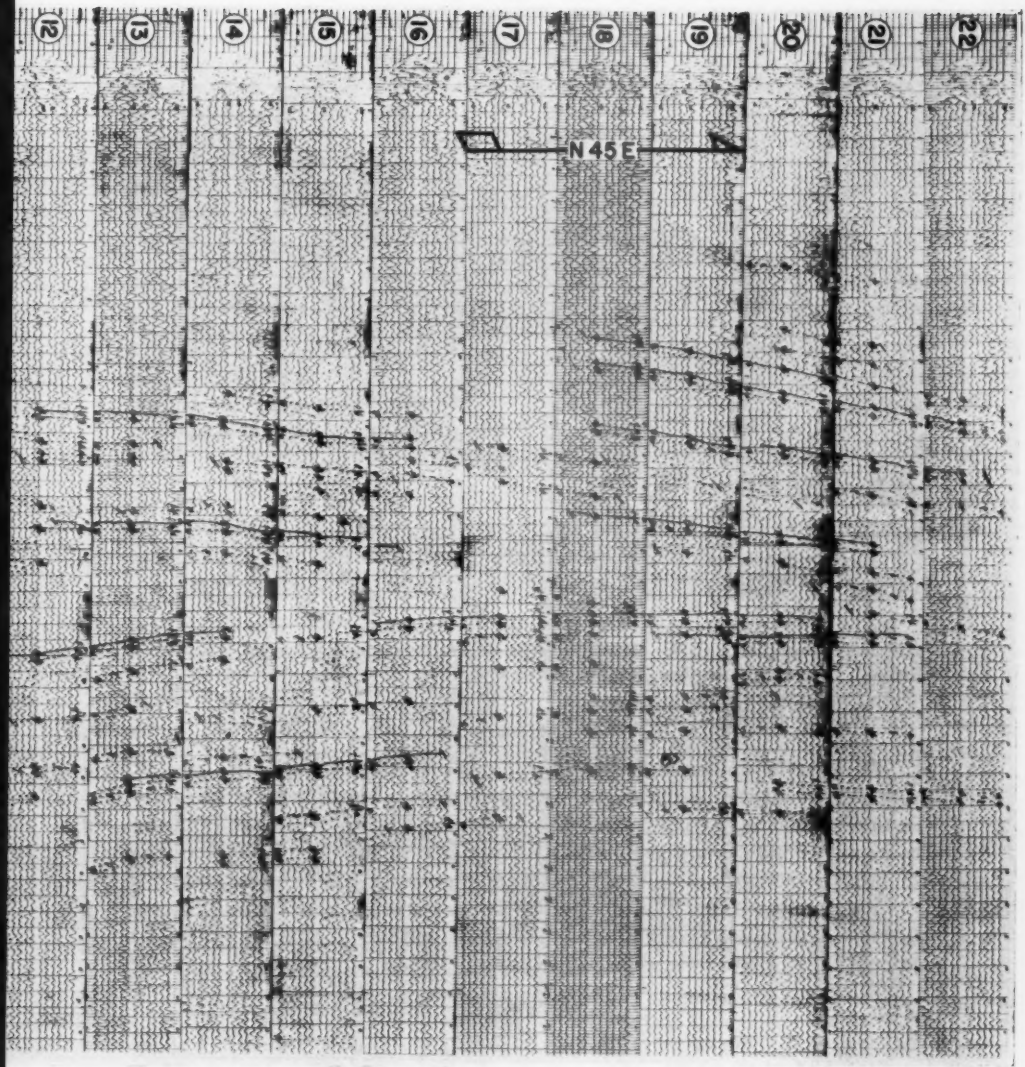


FIG. 3. The seismic records from which the cross-section in Figure 2 was prepar
appears like an ordinary section of sedimentary formations, the



Reflections often show good quality and persistence. Though the record section
ections are concluded to arise from pre-Cambrian igneous layers.

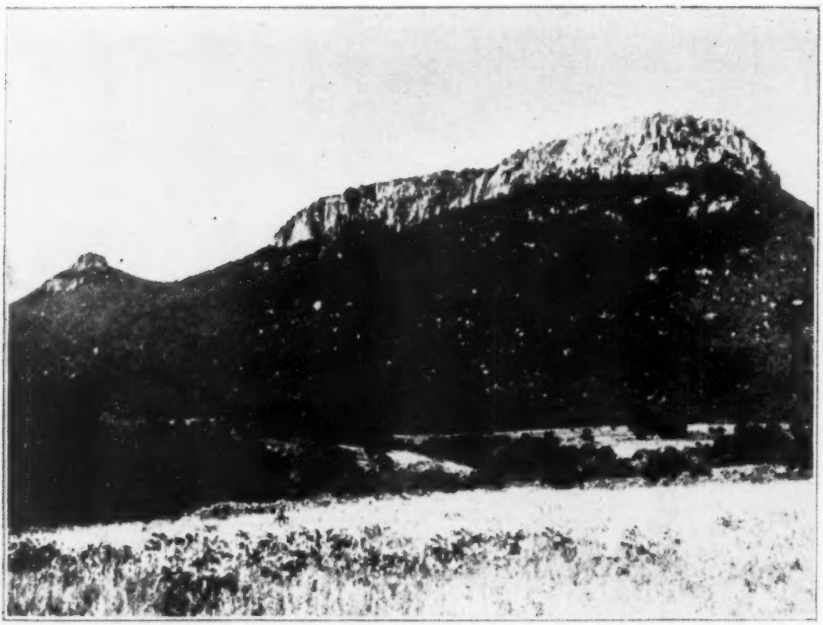


FIG. 4. Mount Sheridan in the Wichita Mountains. The mile-long ridge is an igneous silicic layer underlain by gabbroic layers. Resemblance to a sedimentary cap layer is striking. (From M. G. Hoffman, Okla. Geol. Surv., Bull. No. 52, October, 1930.)

CONCLUSION

The Wichita Mountains demonstrate that in some cases the basement complex may exhibit all the seismic ingredients generally associated with sedimentary sections. Acoustic contrasts, relatively gentle and uniform dips, and extensive continuity of individual layers in a large depth interval are the seismic properties of ordinary sedimentary sections, and all are in evidence in the igneous section of the Wichita Mountains. Though such conditions are not expected to be prevalent in igneous sections in general, the fact that they can occur at all is significant and prompts alertness to their recurrence in other provinces.

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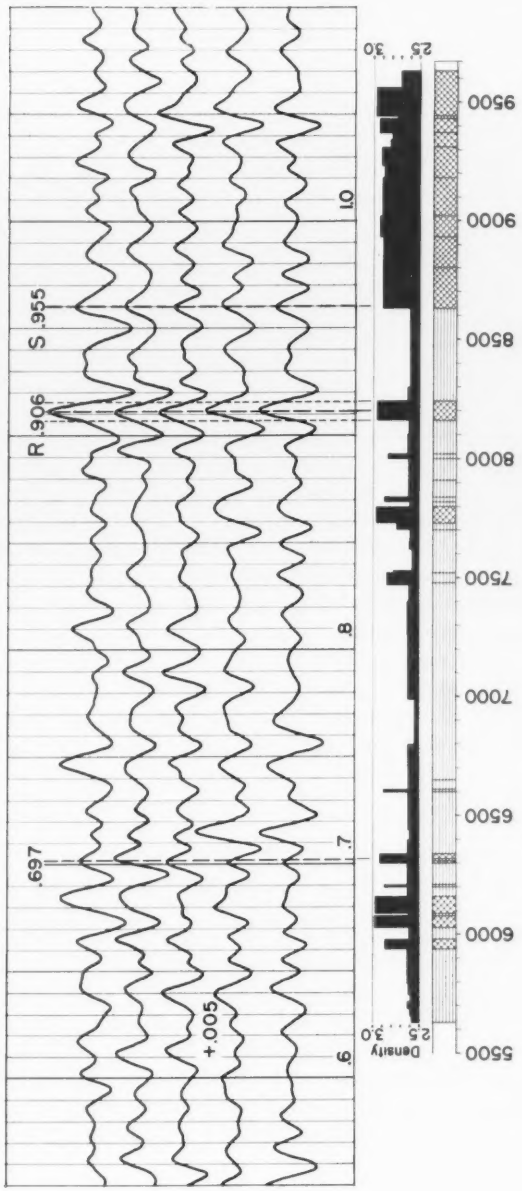


FIG. 5. Comparison between a reflection record and the density log of the igneous section drilled by the Pan American No. 1 Perdasofpy. The two logs were aligned on the R-reflection as shown by applying 40 milliseconds delay correction to that reflection. The depth and time scales in the figure are related by the velocity 18,000 ft/sec. The two outstanding reflections at the location are R and S, and each thus shows a reasonable match with respect to density contrasts between the silicic and gabbroic rocks.

GEOPHYSICS, VOL. XXIV, NO. 3 (JULY, 1959), PP. 426–442, 12 FIGS.

THE MISSISSIPPIAN IN THE ALBERTA PLAINS AND THE REFLECTION SEISMOGRAPH*

G. J. BLUNDUN†

ABSTRACT

The eroded Mississippian surface is the major unconformity in the province of Alberta. To map its erosional highs and lows is most important, because the Mississippian may be productive of hydrocarbons or may cloak the attitude of deeper sediments from which production is sought. This paper deals with the methods of presentation of reflection seismic data to that end, together with a suggested recording instrument technique. Some of the interpretive problems, and the possible significance of Mississippian porosity on the acoustic impedance of its reflection are mentioned.

Maps of similar data, one geological and the other reflection seismic, are presented for comparison. The former is obtained from drilled wells and the latter from reflection shooting performed prior to drilling.

INTRODUCTION

That the Mississippian section may be the hero or the villain of the piece in seismic exploration in the Alberta plains, is well recognized—firstly, because some of its members are productive of hydrocarbons, and, secondly, because it may mask structure in deeper horizons from which production is sought. It becomes most important, therefore, to map its eroded surface—the most significant unconformity in the province. This paper will deal with the methods of presentation of reflection seismic data, devised to that end, utilizing only that information that is tested by wells drilled into the Mississippian, "putting the finger" on the most useful clues therein for the detection of erosional highs and lows. Examples are taken from the Elkton-Harmattan field, producing from the Elkton member of the Mississippian, located some 50 miles north-northwest of Calgary, and about 10 miles east of the foothills disturbed belt, as shown in Figure 1. This is not a case history of that field.

GEOLOGY

Figure 2 illustrates the geologic column in this area where the Cretaceous section rests unconformably on the Mississippian. The three reflections to be referred to frequently arise from the top of the Colorado group, the Home Sand which marks the top of the Basal Quartz member of the Lower Cretaceous in immediate contact with the eroded Mississippian unconformity, and that from the eroded Mississippian surface itself. Quality-wise, the reflections arising from the top of the Colorado, Mississippian, and Cambrian are good; those from the Lower Cretaceous, and Devonian only fair at best, while that from the Home Sand, or top of the Basal Quartz, deteriorates over much of the area.

* Paper read at the 28th Annual International Meeting of the Society at San Antonio on October 13, 1958. Manuscript received by the Editor December 1, 1958.

† Home Oil Company Limited, Calgary, Alberta, Canada.

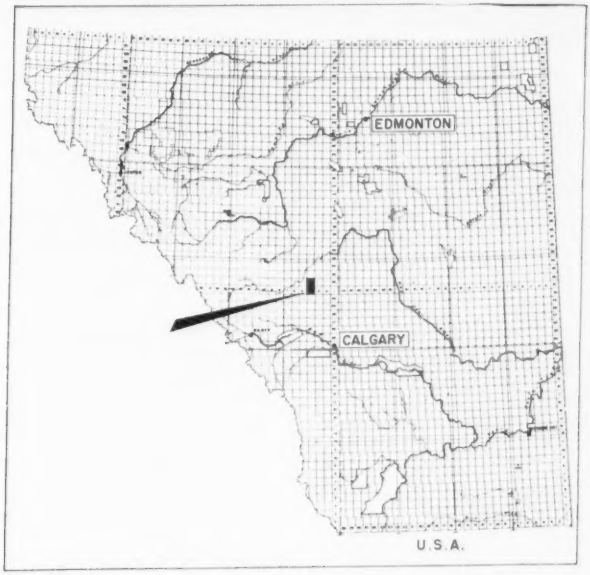


FIG. 1. Location of the Elkton-Harmattan area in the province of Alberta.

Figure 3 illustrates the Mississippian section in the Elkton-Harmattan area, which wedges out completely with progression eastward across the province until the Lower Cretaceous lies unconformably on the Devonian. The regional dip of the Mississippian is southwestward toward the mountain front at the rate of about 50 ft to the mile. This figure will also serve as an illustration of the typical stratigraphic trap sought on the eroded Mississippian surface in the Alberta plains, where a porous member is truncated up-dip by erosion. The two significant members of the Mississippian which may become the erosional surface in this area are the Elkton and the Shunda. Without giving a complete geological description of each, suffice it to say that the Elkton is a dolomite with an average porosity of 10.13 percent, good permeability, with an average thickness over the area of 54 ft, varying from 0 to 157 ft. It is the Mississippian reservoir for hydrocarbons here. The underlying Shunda is an unclean formation of argillaceous dolomite and limestone, with siltstone stringers and inter-bedded shales, non-permeable, with very poor porosity, if any. Hydrocarbon accumulation in this area is controlled, therefore, by up-dip erosional truncation of the Elkton member, which erosion may reach well down into the Shunda. The geophysical problem, therefore, becomes that of mapping the Mississippian unconformity at a depth of 9,000 ft to detect the eroded ridges and trenches, the former of which may be productive.

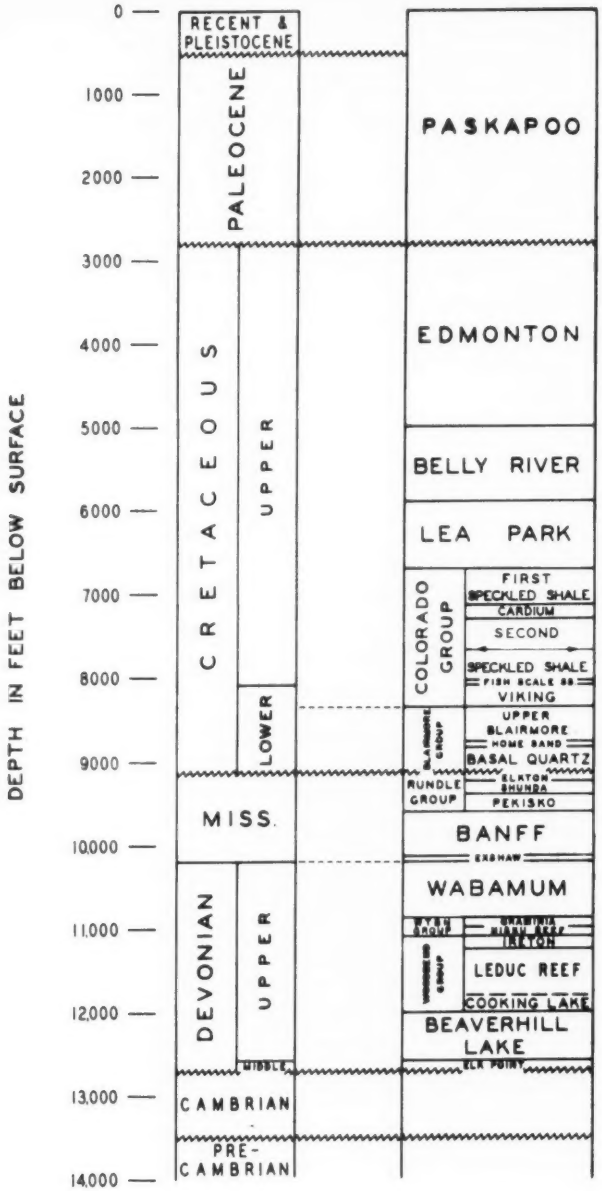


FIG. 2. The geologic column in the Elkton-Harmattan area.

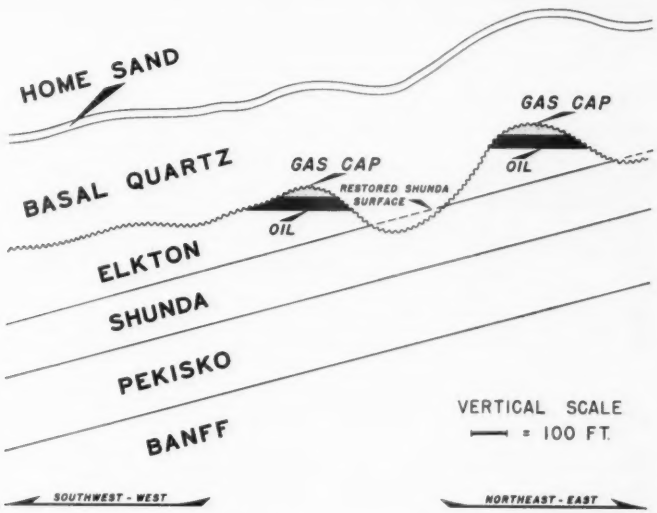


FIG. 3. Typical section through the Mississippian unconformity, and stratigraphic trap created by erosional truncation up-dip of the porous Mississippian member.

REFLECTION SEISMIC

Reflection seismic data available for use in this paper were recorded during 1955 and 1956, without benefit of magnetic tape, using two different sets of conventional recording instruments with the usual automatic volume control, and selective filtering. Shotpoint spacing is quarter-mile, with three geophones per group on one crew, and four per group on the other. Shot depths recorded were normally 80 ft or less, with weathering no particular problem.

Shown in Figure 4 is a continuous line of reflection records with reflections picked that arise from the Colorado, Home Sand, the Mississippian unconformity, and the Cambrian. Troughs are picked for all but the Mississippian, which is read on a peak throughout. The most significant points to note here are that the the Home Sand reflection commences as a phase on the left-hand side to develop into a full leg to the right, and, the distinct separation that occurs between it and that from the Mississippian, progressing from left to right. This is the place to point up the significance of watching for phases to develop into full-blown cycles, which in this instance represents an increase of more than 100 ft in the thickness of the Basal Quartz section—off an eroded Mississippian high into a low. Instrumentwise, therefore, the less active the automatic volume control, the better, with two important reflections so close together. The filtering cut-off should be no more than single-stage on the low-cut side. Although these were recorded with 10 lb of dynamite, the less the better for this type of definition.

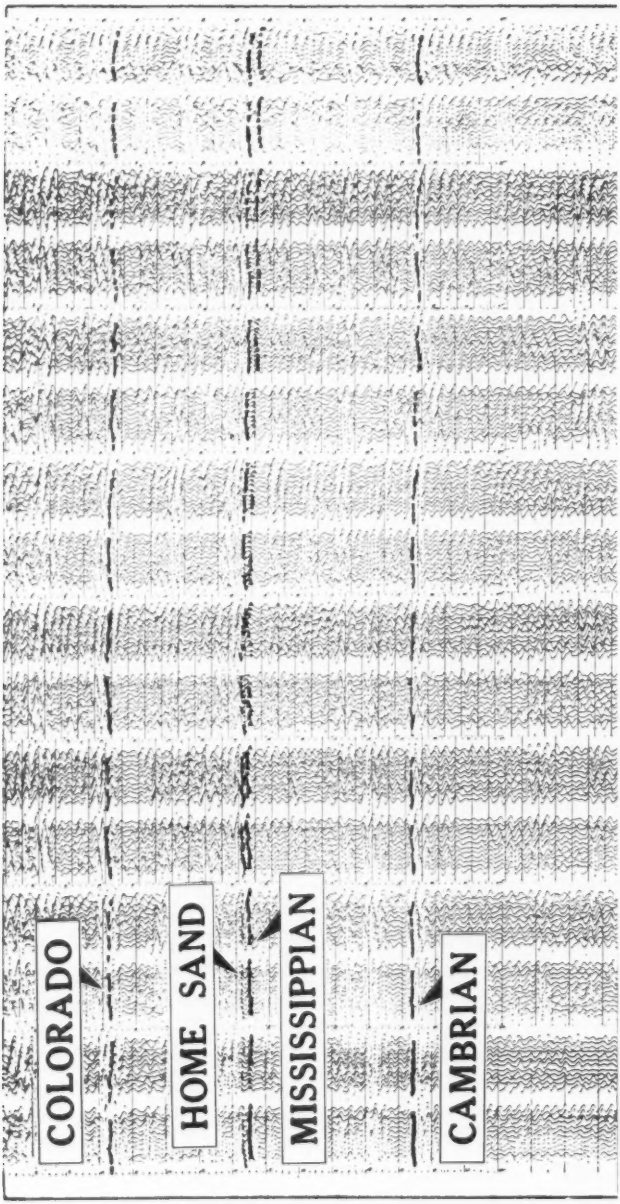


FIG. 4. Specimen reflection records.

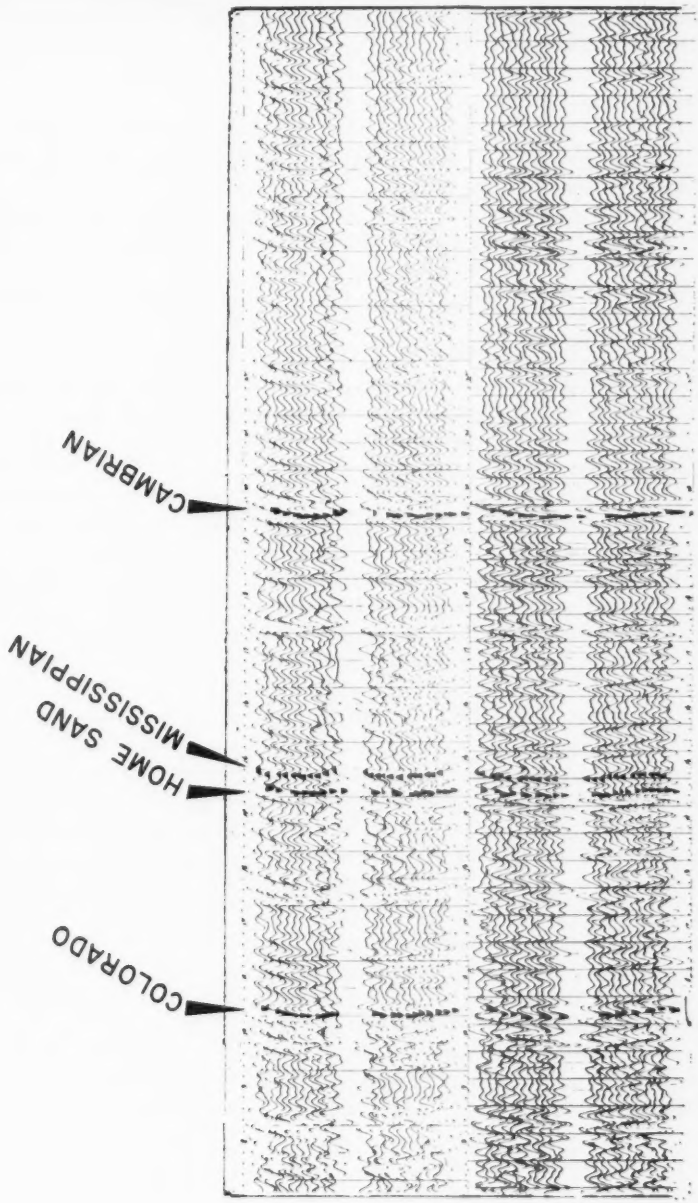


FIG. 5. Expanded view of the two right-hand records in Figure 4.

An expanded presentation of the two right-hand records of Figure 4, for greater ease of inspection, is shown in Figure 5.

The profile of reflection records in Figure 4 is presented in time section form in Figure 6. The following observations are pertinent:

(a) The relatively flat attitude of the Colorado and Cambrian reflections.

(b) The increased dip from left to right of the Mississippian, presenting, therefore, an increased section of Basal Quartz.

The Devonian and Cambrian reflections are not utilized because they have not been sufficiently tested by drilling; the reflection from the Lower Cretaceous is much poorer than that from the Colorado.

Shotpoints 342 and 343 are adjacent to the oil discovery well in the Harmattan field.

GEOLOGICAL VS. REFLECTION SEISMIC

Before reviewing the next few figures of comparative maps, one from reflection seismic data and the other geological from drilled wells, it should be observed that only three wells, separated by 6 to 12 miles from one another, had been drilled prior to any reflection shooting used in this paper. Most of the wells were drilled after the seismic program had been completed. In these comparisons, reflection data utilized are only those from the Colorado, Home Sand, and the Mississippian unconformity. The efficacy of their use to delineate the eroded Mississippian unconformity before drilling should be proportional to its similarity on a map, or maps, contoured from geological data after the wells are drilled.

Figure 7 is a comparison of two maps of the eroded Mississippian surface, the one on the left from well data and that on the right from reflection. The latter was constructed in two steps:

(a) Contouring a map of the lateral distribution of the average vertical velocity from the reflection datum plane to the eroded Mississippian surface.

(b) Calculation of the subsea depths at the shotpoints by the use of the interpolated average vertical velocity pertinent there—tedious, but regionally correct.

In addition to comparing the maps for the location of the respective contours, the position of the two oilfields, Harmattan, and East Harmattan, both producing from the Elkton member of the Mississippian, should be observed. A different gas/oil contact elevation exists for each, −5,360 ft for the former and −4,970 ft for the latter, which implies that these fields must be separated by erosional truncation of the porous Elkton member. This inference is shown geologically, and supported by the syncline between them on the reflection seismic map. The oil/water contact elevation for the Harmattan field is −5,442 ft, but none has yet been found for the East Harmattan field. The water table elevation about the single gas well at the bottom of the geological map, i.e., −5,355 ft, differs from that of the Harmattan field—once again implying separation by erosional truncation of the porous reservoir rock, which is not too well supported by reflection. For the guidance of those responsible for development drilling, knowledge of the locations of the oil/water and gas/oil contact elevations is most important.

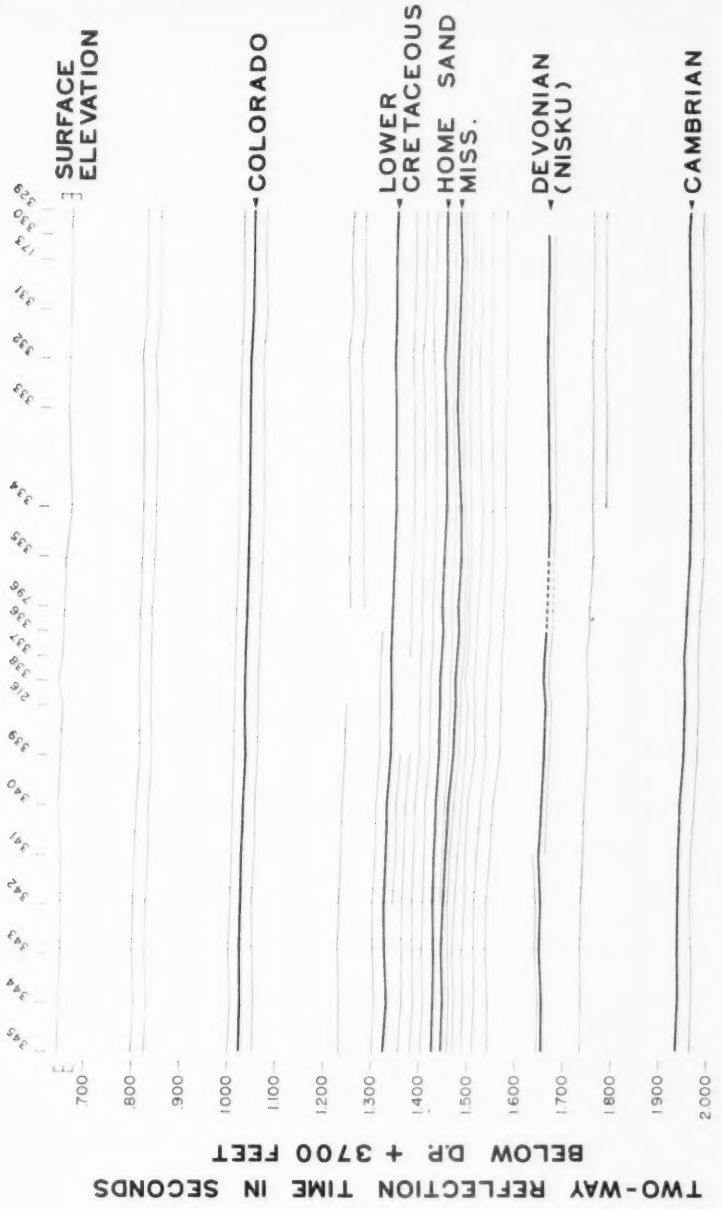
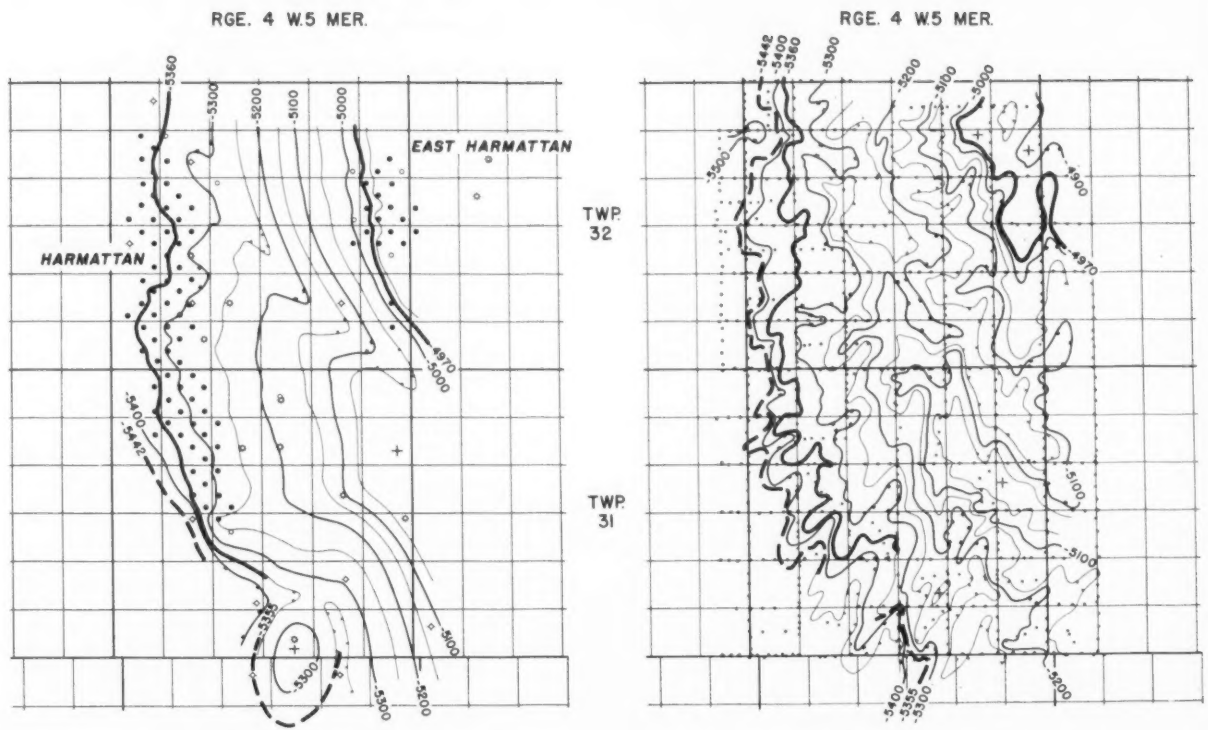


FIG. 6. Specimen reflection records of Figure 4 in time-section form.



GEOLOGICAL REFLECTION SEISMIC

FIG. 7. The Eroded Mississippian surface, depths in feet subsea, contoured in 50-ft intervals. - - - Oil/water contact; — gas/oil contact.

A comparison of the thickness of the Colorado-Mississippian section, geologically in feet and seismically in two-way time, is illustrated in Figure 8. The weighted contours from map to map represent about the same interval in feet. An erosional high on the Mississippian unconformity must be supported by thinning in the Cretaceous section overlying it—the greater the amount of Cretaceous material included in such an isopach, the greater should be the evidence of compaction of it over the Mississippian ridge. Plus signs indicate thin, anomalous areas, and negative signs the thick, unfavorable areas—not necessarily the same quantitatively from one map to the other. Evidence of erosional truncation of the porous Mississippian reservoir between the two oil fields, and the lone gas well at the bottom of the geological map, is apparent, supported by reflection seismic data. In any case, this particular isopach has proven to be more reliable than other isopach combinations.

A similar contrast representing the thickness of the Basal Quartz section immediately overlying the unconformity is shown in Figure 9. Once again, plus signs indicate thins, and negative signs thick areas. Because of the varying quality of the reflection from the Home Sand at the top of the Basal Quartz, this isopach is not nearly so reliable as that of the Colorado-Mississippian. Nevertheless, the data over the Harmattan field compares well, and the implied truncation from East Harmattan is supported seismically.

Another device that has proven most useful is an Elkton thickness map, possibly better termed Post-Shunda, constructed from a combination of geological and reflection data, as represented in Figure 10. To derive the data for the geological map the regional contours on the Shunda surface, restored where erosion into it has occurred, are superimposed on the map of the eroded Mississippian surface, all information taken from wells drilled into the Shunda. The subsea depth at the Mississippian unconformity is then subtracted from that of the Shunda, the resulting sum representing possible productive Elkton thickness where the sign is positive and depth of erosion into the Shunda where negative. The reflection seismic map to the right in Figure 10 is constructed similarly by superimposition of the geological, regional Shunda contours on the reflection depth map of the eroded Mississippian surface. The same subtraction process is then performed, interpolating for depths to the Shunda surface at each shotpoint. In Figure 10, plus signs indicate thickness of porous Elkton, and negative signs, erosion into the Shunda.

Once again, the definition of erosional truncation between some of the productive areas is evident. Quantitatively, the agreement between the two sets of data is best over the productive areas. For the evaluation of land, and estimate of production prior to drilling, this map is most useful. It may be stated that all maps as illustrated, with the exception of the Basal Quartz thickness, have been carried over an area approximating 20 townships, with a better-than-average success ratio.

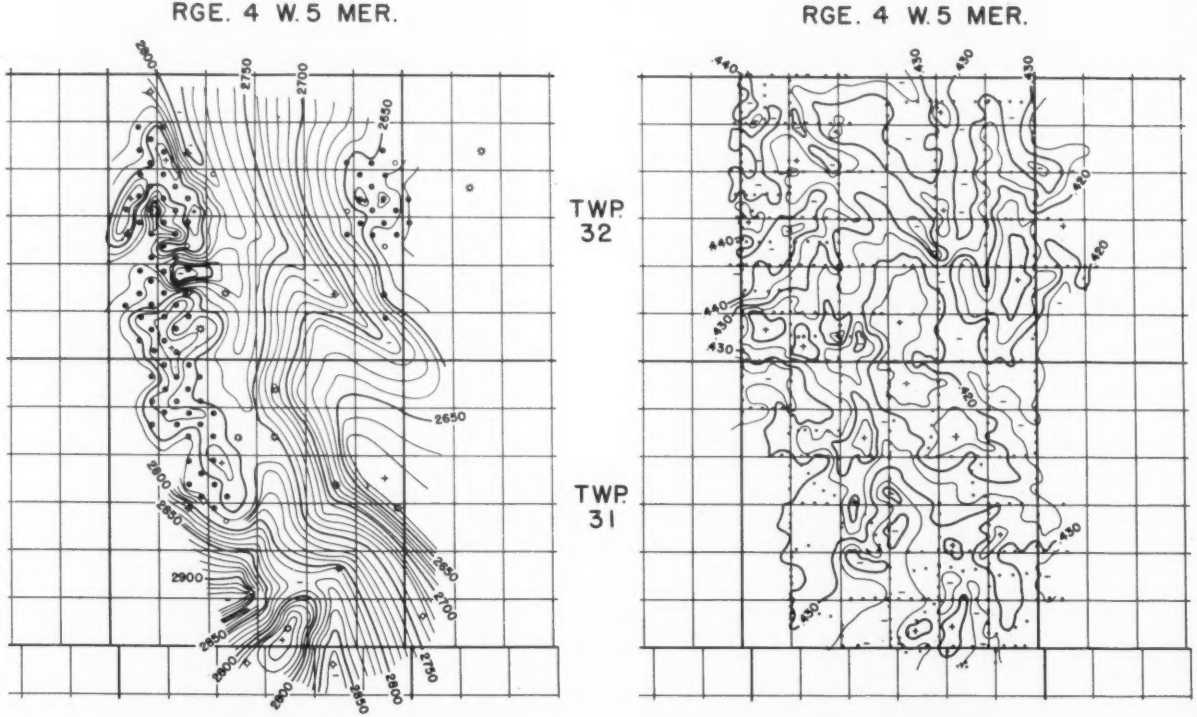


FIG. 8. The Colorado-Mississippian thickness, the geological data contoured in 10-ft intervals, and the reflection seismic, 0.005 sec.

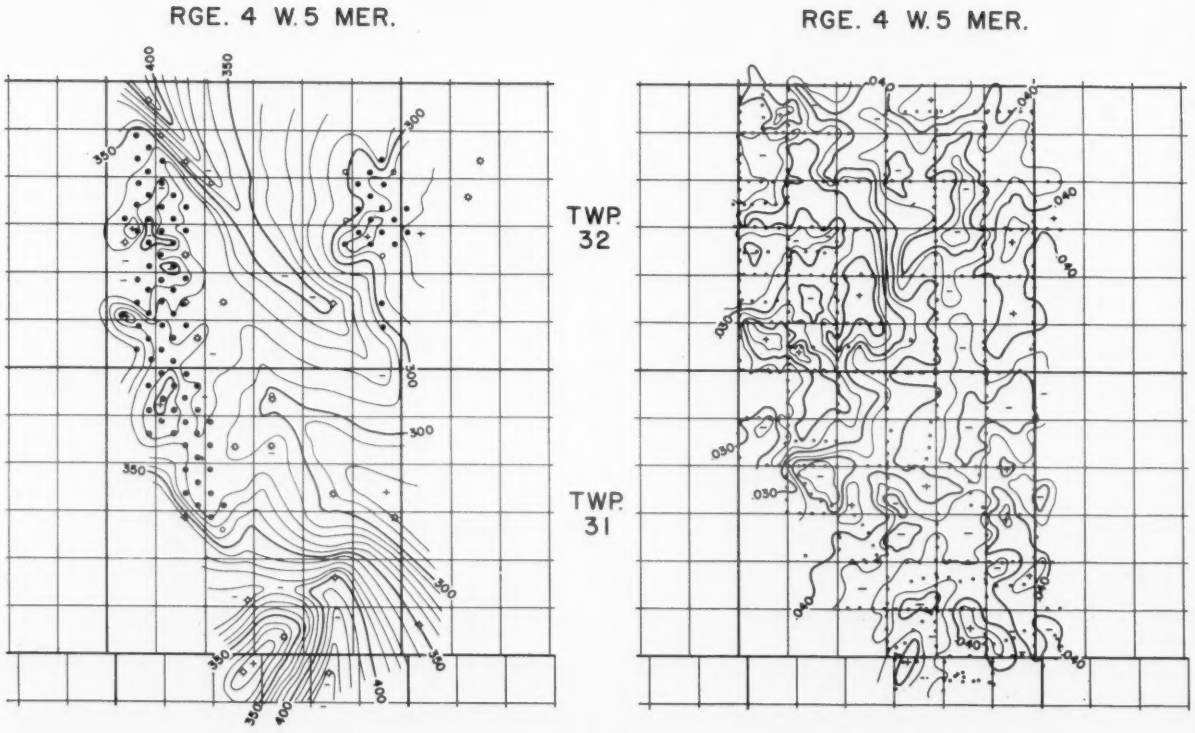


FIG. 9. The Basal Quartz thickness, the geological data contoured in 10-ft intervals, and the reflection seismic, 0.005 sec.

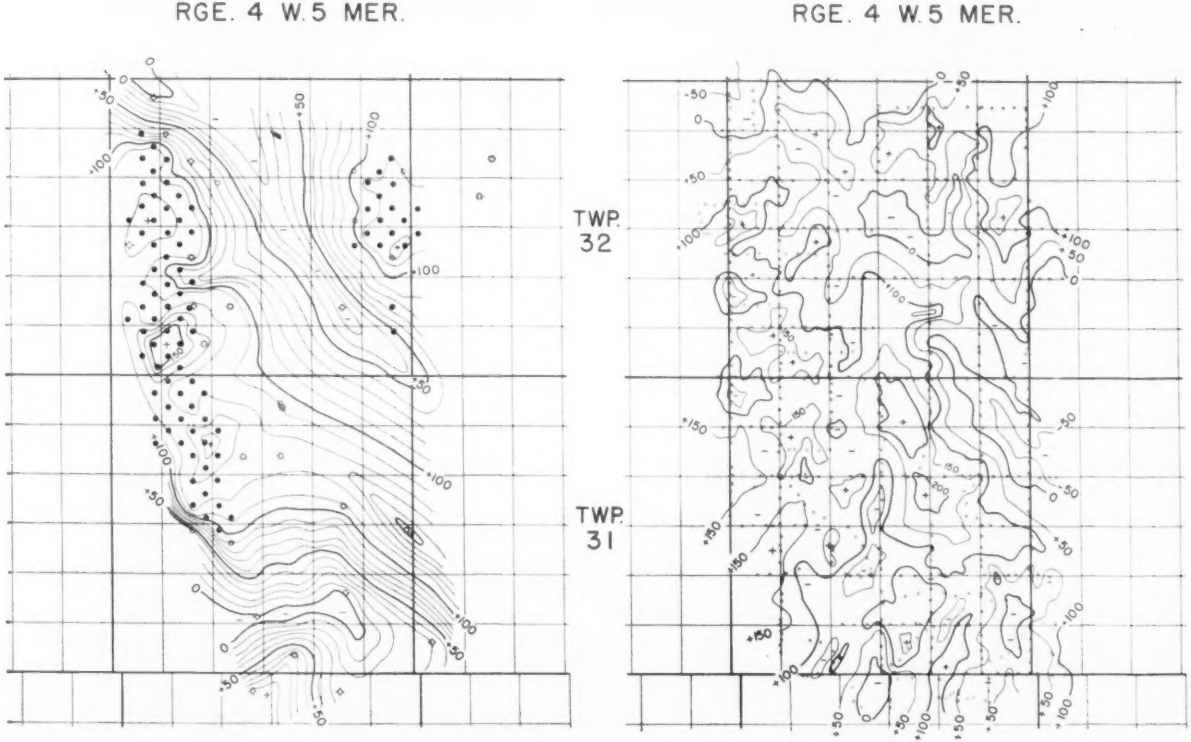


FIG. 10. The Post-Shunda thickness, the geological data contoured in 10-ft intervals, and the reflection seismic, 50 ft.

POROSITY

Figure 11 represents the continuous velocities through the Mississippian unconformity taken from four wells in the area: Canadian Superior O.W.O. Crown Coleman 6–20, a water bearing dry hole, about 6 miles to the southwest of the Harmattan producing area; Home C. & E. Elkton 15–17, a water bearing dry hole at the southwest fringe of the same field; O.W.O. Harmattan 9-5, a capped gas well in the field; and Hunt Home Canadian Superior Didsbury 10-9, another dry hole, about 13 miles east of the field. All curves are taken at the Home Sand level for a common reference plane, interval velocities, Vi, to be read in thousands of feet per second. The two outside wells in Figure 11 were drilled into the Banff formation, but the center two to the Shunda only. The Elkton member has been removed completely by erosion at the Hunt Home Canadian Superior Didsbury well. Some doubt has been expressed among geophysicists that the eroded Mississippian surface in this area could be mapped, and in support they have pointed to the lack of a sharp velocity discontinuity at the erosional surface as exemplified in the three wells to the left in Figure 11. The one to the right meets the discontinuity requirement. Nevertheless, the reflection from the unconformity ties the drilled depths. Solid portions of the curves within the Elkton formation define effective porosity. It is suggested that a density discontinuity, in these cases a sharp decrease from Basal Quartz to Mississippian, because of effective porosity in the latter, is a much more significant factor than has been realized. The map of the top of the main porosity within or at the top of the Elkton compares favorably with that of the erosional surface constructed from reflection seismic data (see Figure 12).

The location and convolutions of the contours over the producing fields, i.e., those annotated −5,300, −5,350, −5,400, and −5,000, compare reasonably well from map to map. The best ties between geological and seismic Mississippian tops have usually occurred where an average section, or better, of effective porosity in the Elkton exists. Until more density logs are run, together with continuous velocity logs through the Mississippian unconformity, the hypothesis that porosity discontinuities are as significant as velocity discontinuities in determining the reflection coefficient, cannot be substantiated. Subsequent synthetic reflection records should be a useful study.

Referring again to Figure 11, in particular to the O.W.O. Harmattan 9-5 well, it is observed that the bottom 30 ft of Elkton, in immediate contact with the Shunda, is not porous. A sharp facies change may occur within the Elkton in that the porous dolomite may be replaced by non-porous and non-permeable limestone, still a part of the Post-Shunda section. As yet this facies change, which may be only local in extent, has been undetectable.

SUMMARY

In summary, the technique of recording and presentation of reflection seismic

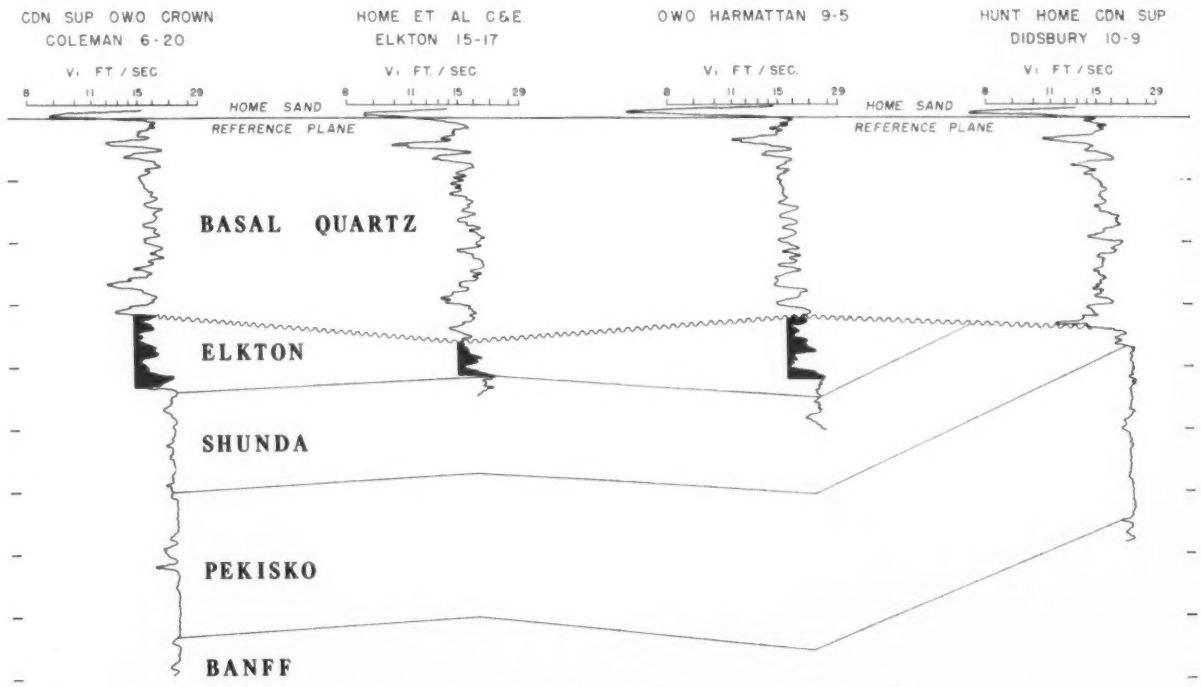


FIG. 11. Continuous velocities (Vi) in thousands of ft per sec through the Mississippian unconformity.

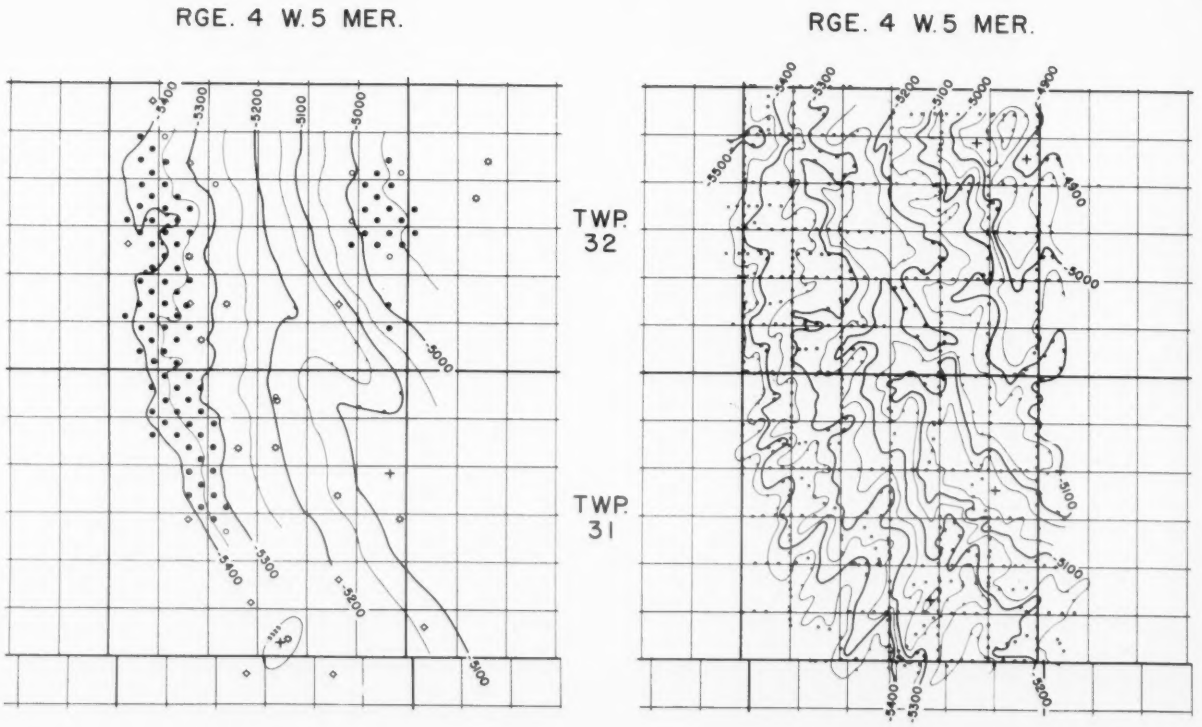


FIG. 12. Porosity and reflection, both contoured in 50-ft intervals. The geological map represents the top of the main porosity in the Elkton member of the Mississippian, and the reflection seismic, the eroded Mississippian surface.

data suggested for definition of the eroded Mississippian surface in the Alberta plains is as follows:

(a) To obtain the best quality data, operate the recording instruments with as little activation of automatic volume control as possible, a reasonably broad filter pass band, and minimum size dynamite charges. Playback selections from magnetic tape should be most useful.

(b) Construct a depth map, measured in feet, of the eroded Mississippian surface, regionally correct.

(c) Without fail, refer to at least the Colorado-Mississippian isopach for evidence of thinning of the Cretaceous section coincident with erosional highs on the Mississippian surface.

(d) Construct an Elkton, or Post-Shunda, thickness map for evaluation purposes.

(e) Adequate reflection seismic control is mandatory when dealing with an eroded surface; it is far cheaper to shoot first inside the section selected for a well site than to drill a dry hole.

In conclusion, the ultimate primary recovery of oil in the Mississippian reservoir of the Harmattan field is estimated at 65 million barrels and the oil in place at 218 million barrels—a substantial recompense; no doubt there are more of these on the Alberta plains.

ACKNOWLEDGMENT

The author wishes to thank the Hunt Oil Company for permission to publish a portion of the continuous velocity log run in its Didsbury well, and the Home Oil Company for permission to publish this paper.

GEOPHYSICS, VOL. XXIV, NO. 3 (JULY, 1959), PP. 443-450, 5 FIGS.

A COMPARISON OF WELL VELOCITY METHODS IN SOUTH TEXAS*

A. B. WOOD†

ABSTRACT

This velocity study is limited to data from one well in South Texas. Two short-interval velocity logging methods compared with conventional seismic geophone data show large discrepancies. The Shell short-interval velocity log agrees within close limits to the conventional seismic data except for the lower 4,000 ft. The indicated delay times for the upper 2,000 ft of this 4,000-ft interval are short by 6.5 percent, and indicated delay times for the lower 2,000 ft are short by 4.0 percent. The Schlumberger Sonic Velocity Log, limited in this survey to the bottom 4,200 ft of hole, indicated delay times larger than the seismic time by more than 5 percent. There is a difference of approximately 9 percent between the two velocity logs, even though the tools were of similar dimensions. The spacing between detectors was three feet, and the distance from transmitter to near receiver was four feet for the Shell tool and three feet for the Schlumberger tool.

An analysis of the basic data is necessary to resolve these discrepancies. There is no check on the Sonic data in its present form, but a thorough study of the Shell Oscillogram log and conventional seismic data for errors fails to explain the 6.5-percent and 4-percent discrepancies in the Shell short-interval velocity data. The conclusion must be drawn that these discrepancies are real. This survey demonstrates the necessity to check short-interval velocity logging with conventional seismic shots to maintain acceptable seismic well velocity standards.

INTRODUCTION

Today, considerable effort and thinking on well velocity control brings up the matter of the discrepancies one may encounter in using various methods to obtain such data. Adherence to acceptable seismic well velocity standards is now more important than ever, due to the increase in the number of well surveys being made. This is especially true when large discrepancies as described in this paper are encountered.

A specific velocity study was made by the Shell Oil Company in the South Texas Gulf Coast region in May, 1958. This study is limited to data in one well of Miocene and Oligocene formations, the Oligocene consisting of Frio and Vicksburg sands and shales. The purpose of the study was to compare carefully conventional seismic geophone results with short-interval velocity logging. A comparison of results from Shell's short-interval velocity method with Schlumberger's velocity system, Sonic logging, was also of importance. Short-interval velocity logging is known as Continuous Velocity Logging, Acoustic, and Sonic logging, the latter two being trade names.

INSTRUMENTATION DETAILS

A few details of the two different short-interval velocity methods will first be described. Figure 1 illustrates the type logs obtained with Shell's logging equip-

* Paper read at the 28th Annual International Meeting of the Society at San Antonio on October 15, 1958. Manuscript received by the Editor December 30, 1958.

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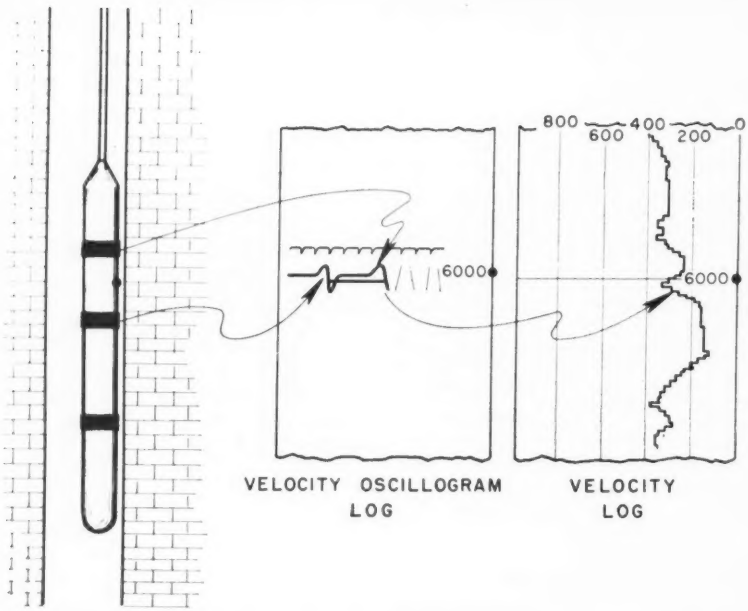

FIG. 1. Layout of Shell's borehole velocity tool, illustrating the recorded velocity oscillogram log and velocity log in microseconds at 6,000 ft.

ment. At the left, the Shell borehole tool for this particular survey had its sound source located at the bottom of the two-receiver sonde, 4 ft from the first detector. The distance between the two detectors was 3 ft. The oscillogram log is a recording of the signals received by each of the detectors. The signals of both detectors are recorded on the oscillogram trace for each observation of the survey.

Indicated delay time picks for each observation may be read on the oscillogram log and used to calibrate the velocity log during the time of running the survey, and/or to correct the data when necessary at any time later. Microsecond time scales are given at regular intervals on this oscillogram log. These markers represent time intervals of 100 microseconds, and the time scale on the trace is substantially linear.

The velocity log is run simultaneously with the oscillogram log, as is indicated on Figure 1 at a 6,000-ft depth. Both records are made at the surface. Figure 2 shows a portion of these two logs from the well survey discussed. On the oscillogram log the signals from the first detector of each oscillograph are shown in vertical alignment on the left. Second detector signals indicate delay time variations as these time values are recorded on the velocity log. The velocity log for this survey was recorded in microseconds per foot on two different linear scales as illustrated.

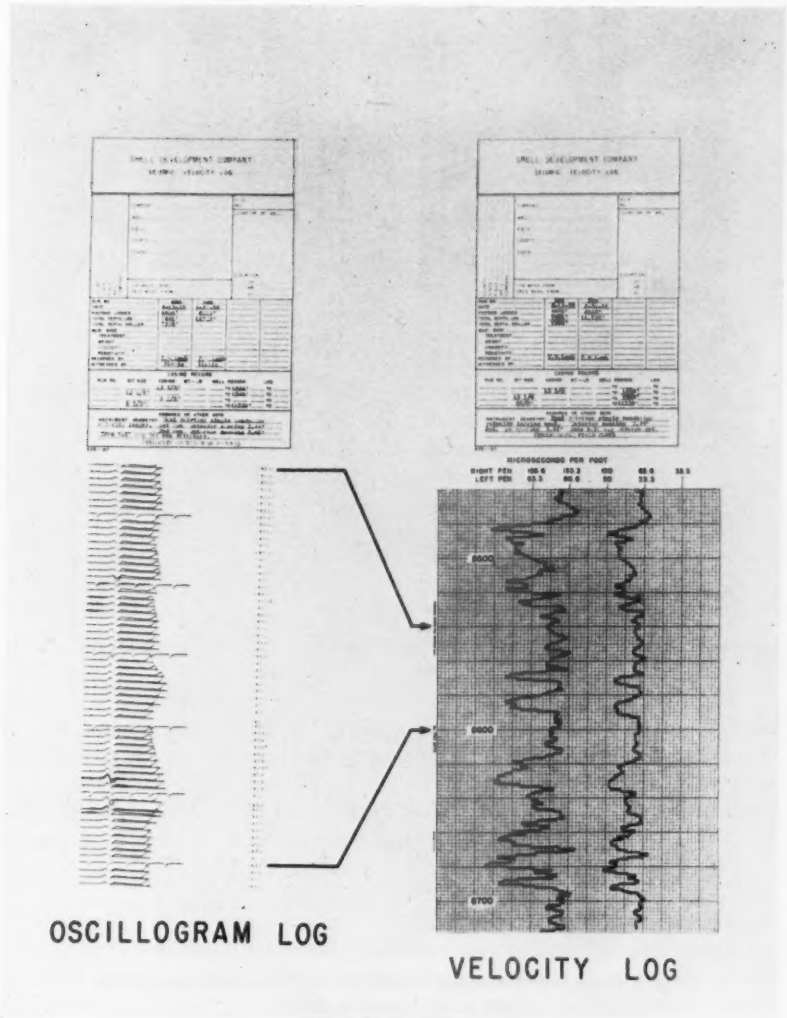

FIG. 2. Example of Shell interval velocity data from 8,500 to 8,700 ft under discussion.

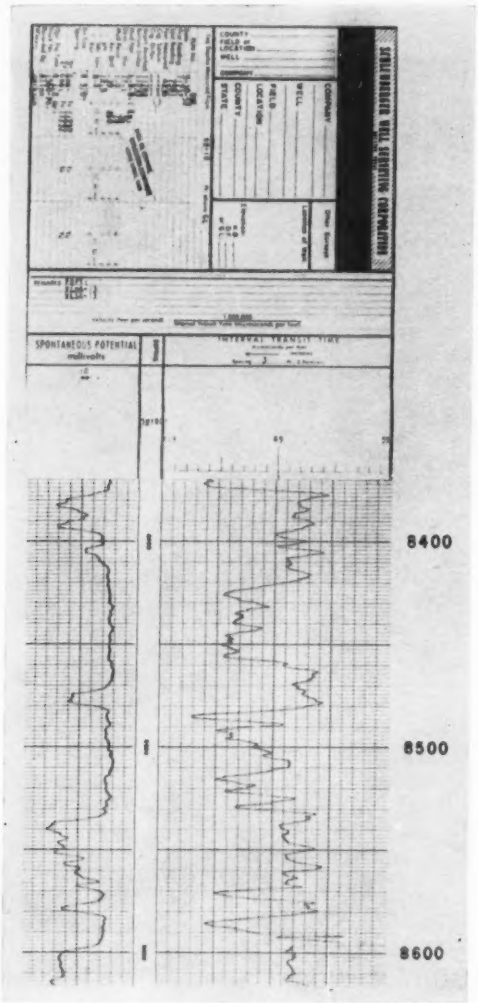

FIG. 3. Example of Schlumberger's S.P. curve and Sonic log from 8,400 to 8,600 ft of the well data discussed.

A layout of Schlumberger's Sonic log is given in Figure 3. To the left is recorded the usual spontaneous potential curve expressed in millivolts. The Sonic log, on the right side, is recorded with an interval transit time scale given in microseconds per foot. The Sonic log data used in the comparison study was taken from a standard 3-ft log; i.e., the spacing between detectors was 3 ft.

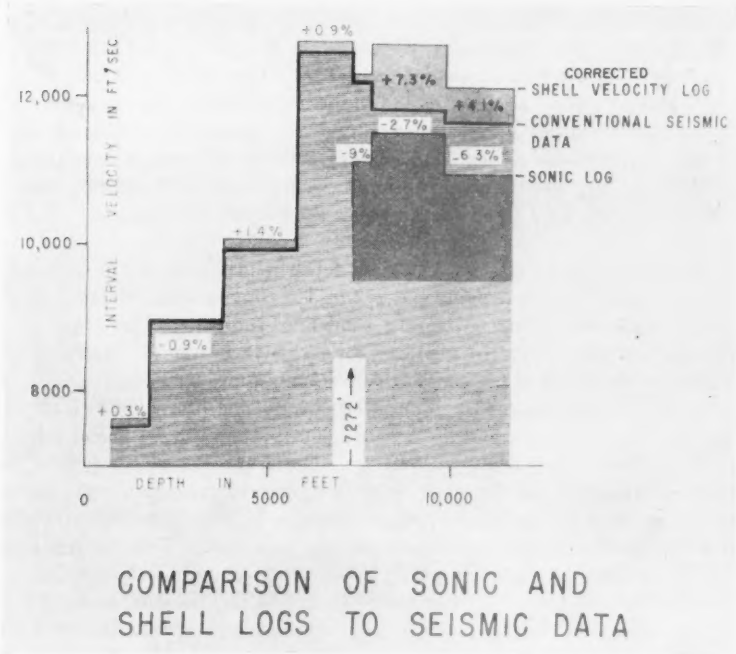

FIG. 4. Graphs of interval velocity averages for each interval checked by conventional seismic shooting. Shell oscillogram log values were used.

The conventional seismic geophone equipment used in this survey included two Shell-type hydrophones and one vertical component velocity geophone. Conventional seismic time breaks of good quality were recorded at each check point. No errors were detected in these data when making a thorough review of the results. The survey is considered reliable and accurate.

DATA OBSERVED

All data for this discussion are shown in Figure 4. Interval velocity averages are plotted versus depth in feet for each interval checked in the well by the conventional seismic shooting. These seismic intervals from datum down to total depth were no greater than 2,000 ft. Conventional seismic results are shown by the continuous heavy black line.

Shell short-interval velocity results are compared with conventional seismic data by shading the differences, with percentage figures indicating the magnitudes of differences. From near-surface depths down to 500 ft below the assumed 7,272-ft tie marker, the Shell short-interval velocity data agrees within 1.4 percent, or within very close limits with the conventional seismic survey. For

the next 2,000-ft interval, however, the short-interval velocity average is 7.3 percent greater than the conventional data. For the deepest portion of the survey, the short-interval velocity average is greater by 4.1 percent.

Sonic logging in this well was limited to the lower 4,200 ft, i.e. below the 7,272-ft tie point. Sonic-interval velocity averages are shown with percentage differences from conventional seismic data. The Sonic velocity average over the shallowest interval was less than conventional seismic data by 9 percent, over the second interval less by 2.7 percent, and over the deepest interval less by 6.3 percent.

Figure 5 is prepared to show the time-depth relationship of the data below the assumed tie or reference point at 7,272 ft. The conventional seismic times are shown as black dots connected with a solid line. Indicated delay times of the short-interval velocity data are averaged for each 100-ft interval. Corrected Shell log times are shorter than the conventional seismic times by 17 milliseconds in a total of 358 milliseconds, or by about 4.8 percent. The first 2,000-ft interval is 6.5 percent shorter in time, and the second 2,000-ft interval is 4.1 percent shorter, most of the discrepancy being within the first interval. Before computing these percentages, the Shell short-interval velocity log times were carefully studied and corrected by using the accompanying oscillograph log, and the Shell equipment used in the survey was examined for other sources of error. No error was found.

The Sonic time data as averaged on this time-depth graph is longer than conventional geophone times by 14 milliseconds in 358 milliseconds, about 4.0 percent. The indicated delay times of the Sonic data are greater than the Shell oscillogram logged delay times by a total of 31 milliseconds, or in 358 milliseconds this is a discrepancy of approximately 8.7 percent. These Sonic log times, taken from the 3-ft log, were checked closely by the operators with the use of a 1-ft Sonic log, by caliper logs, by dip logs, and by all the other types of well logs run in this well. Variations in the borehole diameter were only from 8.7 to 9.2 inches.

Differences between the Shell and Sonic logs are large, and it appears to the author highly improbable that they can be explained on the basis of tool geometry. Spacing between receivers was 3 ft for both tools; the distance from transmitter to near receiver was 4 ft for the Shell tool and 3 ft for the Schlumberger tool. This small difference in transmitter distances will produce negligible differences in first arrival travel paths between receivers in the two cases, even if extensive shale damage exists. This conclusion is supported by the data which indicate discrepancies of about the same magnitude and sign in both sand and shale sections.

At present there is no apparent method for an easy check of Sonic results for absolute values, at the time when the log is run, or afterwards when one wishes to analyze basic data. The seismologist, however, wishes to depend on basic observations. Perhaps closer absolute agreement in delay times can be achieved by some improved calibration method. Certainly, similar well velocity comparisons should be continued until such problems are resolved.

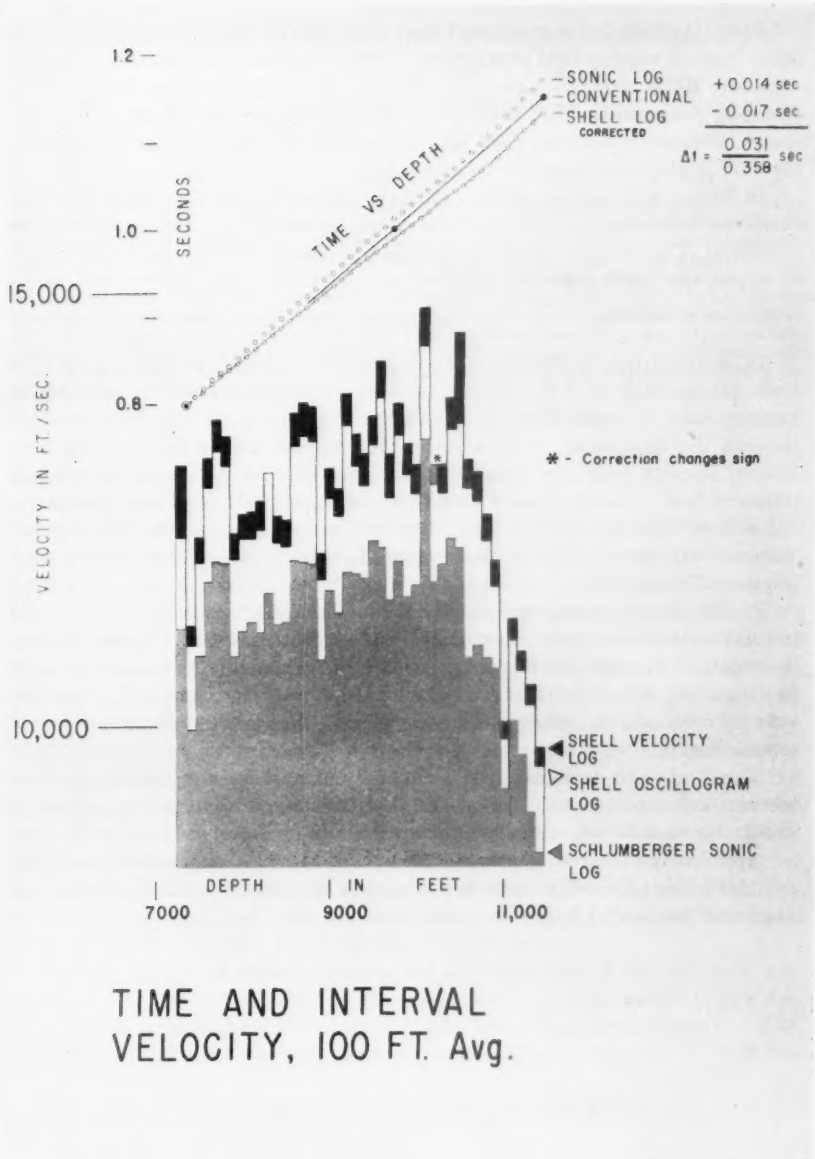

FIG. 5. Graphs of time vs. depth comparisons, and short-interval velocity data comparisons for each 100-ft interval below the 7,272-ft reference point. Shell's oscillogram log values were "hand-picked," i.e., correcting the Shell short-interval velocity log.

Below the time-depth graph on Figure 5, plotted in velocity versus depth are short-interval velocity data averaged over 100-ft intervals. Averaging the velocity data over 100-ft intervals is an accepted procedure by the Southern Seismic Well Shooting Association. Shell oscillogram log readings, or correct log values, are shown. Differences between Shell velocity log and the "hand-picked" Shell oscillogram log graphs average about 1.5 percent.

In Figure 4, it appears that a constant difference exists between the Shell corrected short-interval velocities and Sonic log velocities. This is merely coincidental. The velocity values do not follow as closely when examined on Figure 5, i.e., on the 100-ft interval data.

SUMMARY

In summarizing, an analysis of the basic velocity data is necessary to resolve time discrepancies in well velocity surveys. To obtain accurate short-interval velocity data, it is important to record the original signals that have traveled through the formations. Then a more effective use can be made of the logs. Several velocity tools now transmit these signals to the surface for monitoring purposes, and it would appear that they could easily be recorded. Companies using such tools include the Magnolia Petroleum Company, the Seismograph Service Corporation, Empire Geophysical Incorporated, and the United Geophysical Corporation.

In this survey, a thorough study of the Shell oscillogram velocity log and conventional seismic data fails to explain the 6.5-percent and 4.1-percent time discrepancies encountered in the lowest portion of the well. The conclusion must be drawn that here conditions exist which produce real discrepancies in these two velocity methods, the Shell oscillogram velocity logging and the conventional seismic survey.

This study also demonstrates the necessity to continue supplementing short-interval velocity logs with conventional seismic check shots to be assured of acceptable seismic well velocity standards.

Appreciation is hereby acknowledged to the Shell Oil Company for permission to publish this paper. The writer is indebted to Mr. C. B. Vogel and others of the Shell staff for reading and commenting on the paper.

GEOPHYSICS, VOL. XXIV, NO. 3 (JULY, 1959), PP. 451–464, 8 FIGS.

LATERAL VELOCITY VARIATIONS NEAR BOREHOLES*

WARREN G. HICKS†

ABSTRACT

Difficulties occur in obtaining accurate two-receiver velocity logs in formations sensitive either to damage by exposure to drilling mud or to mechanical stress relief. Some shales are so altered by the drilling operation that their elastic properties are modified. Vertical velocity measured immediately adjacent the boreface is lower than if it were measured at a greater radial distance from the bore. These damaged shales require relatively deep penetration by the acoustic signal; consequently, the transmitter-to-first-receiver spacing in a two-receiver velocity logging system should be long enough to refract the sound waves through virgin formation. Experiments in one predominantly shaly section show a difference of almost 10 percent between times measured using transmitter-to-first-receiver spacing of 4.3 ft compared to 8.8 ft. A limited amount of field data suggest that sodium montmorillonite is the clay type most sensitive to hydration and swelling. Studies of areal prevalence of the shale damage problem are incomplete.

INTRODUCTION

Some years ago, the Magnolia Petroleum Company ran a single-receiver velocity log and geophone survey in a well in McClain County, Oklahoma. The results were both puzzling and disappointing. Integrated travel time recorded by the log was 24 percent greater than that indicated by the geophone survey. The conventional assumption that this delay in signal was caused by borehole cavities was then evaluated. The hole had large cavities. However, even after the cavities were taken into account there was too much time on the log to be explained. The geophone survey was carefully checked and the quality was excellent; signal-to-noise ratio during the logging operation was good; log calibrations were correct. Two years later, two-receiver velocity logs were run in the same area using 4.3-ft spacing between the transmitter and first receiver. According to simple ray-path theory, this 4.3-ft spacing should give zero error in cavities up to 29 inches in diameter in formations with velocity of 8,000 ft per sec. Maximum hole diameter from the caliper log was 19 inches, and yet errors of the order of 5 percent in shaly intervals in the shallow portion of the well were observed. As a result of these and other similar results, we began to suspect formation damage as being the main source of these unusual errors.

In early studies of velocity logging the rock surrounding the well bore was regarded as an infinite medium for the propagation of sound waves. It now appears that in some shales a lateral velocity gradient exists. Sound waves travel at lower speeds near the bore; and, at some greater distance, they propagate at the

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† Magnolia Petroleum Company, Dallas, Texas.

true speed of sound in the shale. This fact enters into the design of two-receiver velocity logging tools because the spacing between the transmitter and first receiver must be great enough for the sound wave to penetrate radially to a sufficient depth to reach undamaged formation. Original calculations indicated that a 4-ft spacing was adequate distance between the transmitter and first receiver to make errors caused by cavities negligible. Shale damage is similar in its effects on velocity, but it may extend about two to six hole diameters. Hence, if the first receiver is spaced too close to the transmitter, shale damage effects are apparent on the log; on the other hand, if it is spaced too far, the signal-to-noise ratio is poor.

Thin bed resolution, of course, is not altered by changing the distance from the transmitter to the first receiver. It is fixed only by the distance between the two receivers.

Kokesh and Blizard (1958), in a paper first presented before the Eleventh Annual Midwestern Exploration Meeting in Tulsa, observed that "there is some evidence that the action of the mud or stress concentration around the bore can change the velocity of the formation." It will be this change in velocity that we shall now consider.

THE WEATHERED LAYER ANALOGY

If we cut a well bore vertically and open it up into a plane surface, then tip it over to a horizontal plane, we may compare it to the surface of the earth. We then have something similar to the familiar weathered layer.

Figure 1 is a time-distance plot of the first arrivals at a prospect in Henderson County, Texas. The geophone spread was 25 to 300 ft; the shot was only 2 ft deep. The apparent velocity (measured as the distance between detectors divided by differences in times of the first arrival) is 1,500 ft per sec for the first five detectors. For greater distances the apparent velocity increases until subweathering velocity of 5,900 ft per sec is reached. In this particular case the first detector should not be less than 175 ft from the shot to measure velocity in the subweathering.

Figure 2 is also a time-distance plot and has a similar shape. This was taken from a logging tool with a sound wave travelling vertically to six detectors. A spot in the well was chosen where formation velocity and borehole size were approximately uniform for a distance of 15 ft; arrival times were measured in this interval. Velocity values for the three most distant points are considered to be in reasonably good agreement and represent true formation velocity. Values for the first two points are anomalously low and reflect the influence of alteration of shale velocity. In this case, the first detector should be 8 ft away from the source to measure true velocity.

There is a strong analogy between vertical measurement of the speed of sound waves in formations surrounding a borehole and the horizontal measurement in the subweathering. In either case the geometry should be arranged so that the sound wave penetrates deeply enough to measure the true velocity.

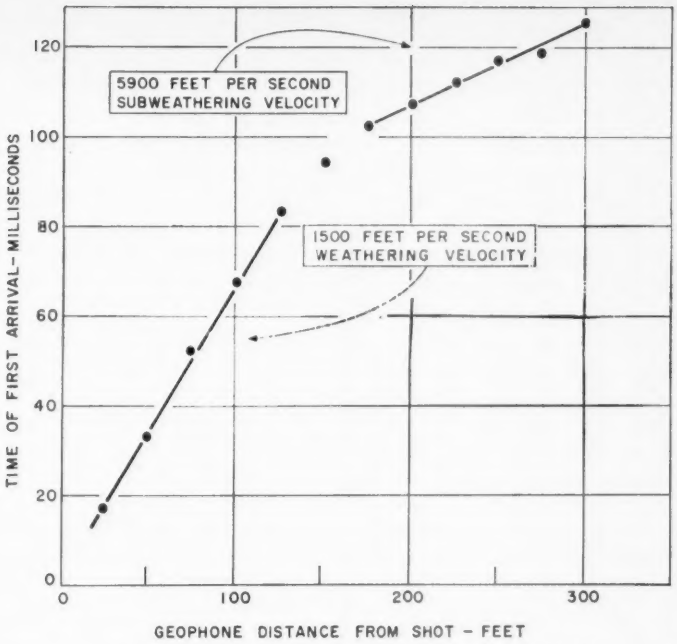

FIG. 1. Effect of weathered layer on propagation of horizontally travelling sound waves. Velocity in the weathered layer is 1,500 ft per sec and in the subweathering is 5,900 ft per sec.

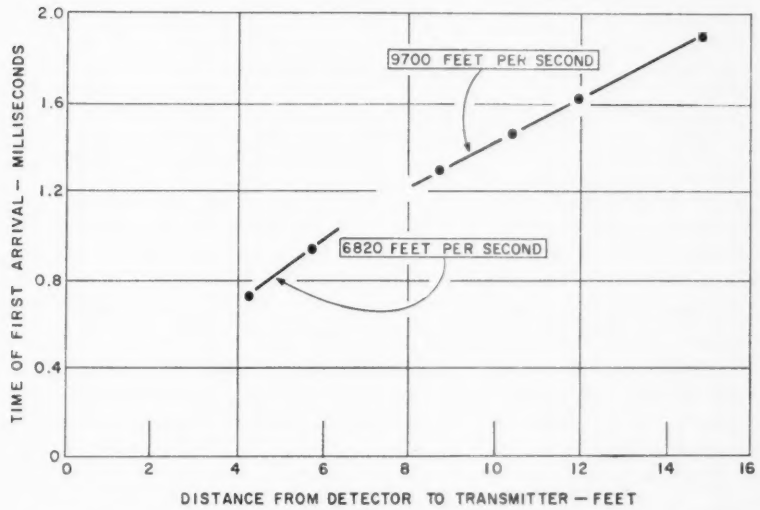

FIG. 2. Effect of shale damage on propagation of vertically travelling sound waves. Velocity near the bore is 6,820 ft per sec and remote from the bore is 9,700 ft per sec.

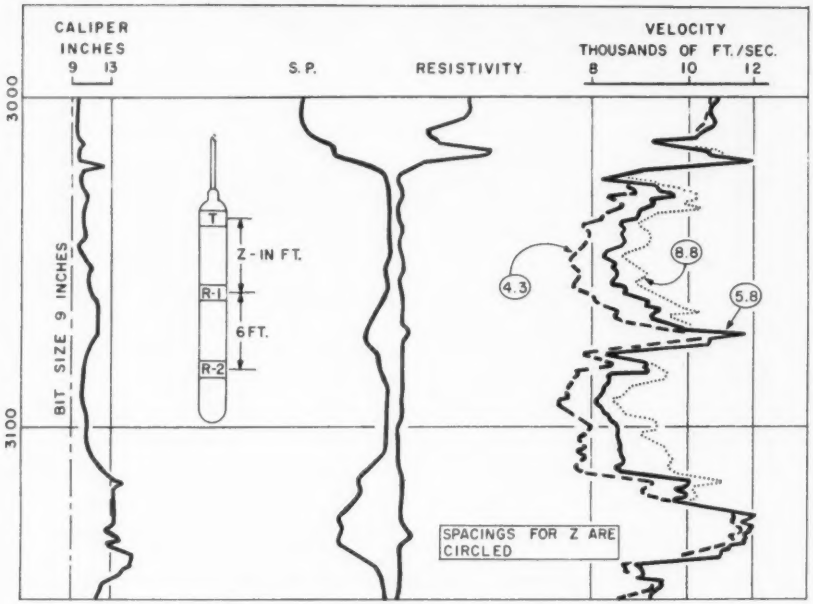

FIG. 3. Effects of changes in transmitter-to-first-receiver distance. All velocity logs have the same spacing between receivers but the transmitter-to-first-receiver distance is changed from 4.3 to 5.8 to 8.8 ft. In shaly intervals the shorter distances read velocities that are too low, but in sandy zones all agree.

FIELD EXPERIMENTS

A special test of the effect of shale damage was made in a well in the Anadarko Basin of Oklahoma. Three different transmitter-to-first-receiver spacings were used: 4.3, 5.8, and 8.8 ft. The span between receivers was held constant at 6.0 ft for all three logging runs. If 4.3 ft is long enough for the transmitter-to-first-receiver spacing, all three runs should be identical within the repeatability of the instrument. A portion of the logs from this well is shown as Figure 3. Duplication of the three curves is reasonably good in the sandier, higher-velocity sections of the log. However, in the shaly sections the logs do not duplicate in absolute velocity measurements. The 4.3-ft spacing reads the lowest velocity, the 5.8-ft spacing intermediate, and the 8.8-ft spacing the highest. These effects are present even though the caliper log indicates that hole diameter is less than 15 inches. In the 300-ft interval from which this example was chosen, integrated times were compared for the different spacings: the 4.3-ft curve reads 9.8 percent more than the 8.8-ft; the 5.8-ft curve reads 3.9 percent greater than the 8.8-ft curve. Overall difference in total travel time between the 4.3- and the 8.8-ft curves from the surface casing to total depth was only 3.5 percent, indicating that not all of the

well was damaged to the same extent. No geophone survey was made in this particular well, but one was available in a diagonal offset well 1,870 ft away. Formation tops in the two wells are very nearly at the same depths and the geophone survey checked the 8.8-ft spacing log to within 0.5 percent error.

Figure 4 is a portion of the log from a South Louisiana well which again illustrates errors caused by having transmitter-to-first-receiver spacing too short. Unfortunately, this was not a controlled experiment and these conclusions were reached only after the logs were run. In this well, a geophone survey and a long interval survey were available to support the log data. The geometry of the logging devices is shown at the side of the figure: Log A is a 4.3×6.0-ft two-receiver curve; Log B is a 3.0×3.0-ft two-receiver curve; and Log C is the 4.3-ft single-receiver curve recorded simultaneously with Log A. Log B has been smoothed by a running average operator to give the appearance of a 6.0-ft spacing for ease of comparison with Log A. As in the previous example, the three curves agree quite well in the sand zones but in the shales the velocities differ with each log. Log A is the highest velocity; Log B is about 400 ft per sec lower in shale zones, and Log C is about 800 ft per sec lower in shales. Figure 5 is a plot of the integrated travel times in this well compared to the long interval survey

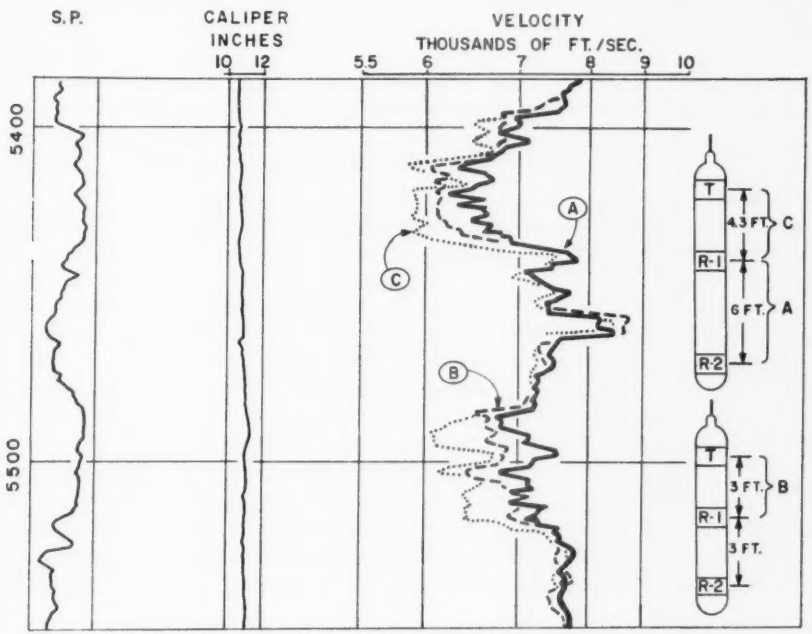

FIG. 4. Effects of changes in receiver spacing. Even though hole diameter is nearly constant the logs only duplicate in sands.

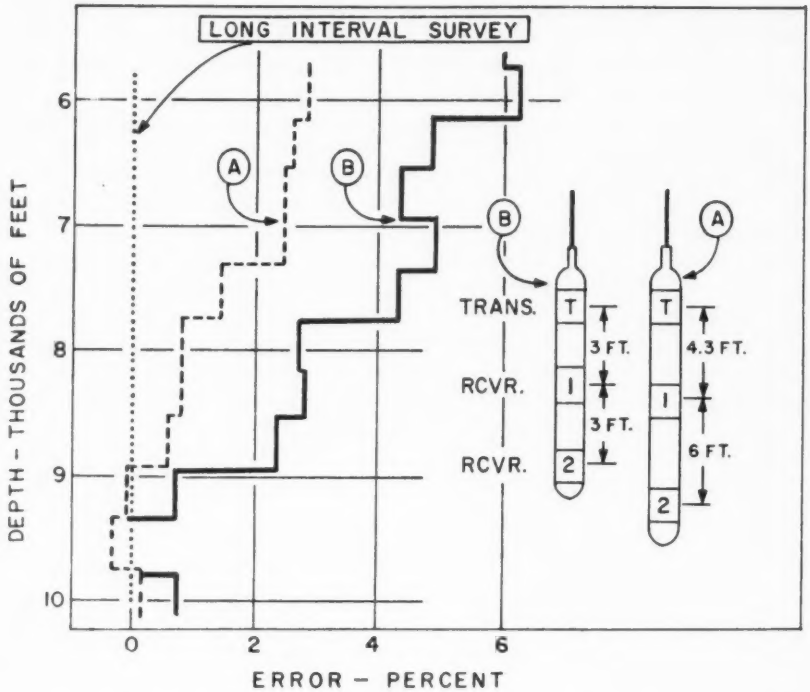

FIG. 5. Integrated log time versus depth for the two-receiver logs illustrated in Figure 4. This is a typical error plot, showing large discrepancies at the top of the uncased portion of the well and gradually decreasing to zero at the bottom.

(Kokesh, 1956).* The significant fact is that both logs show too low velocity even though the hole is essentially true gauge. The major difference between the two-receiver curves is the spacing between receivers: A, using double the spacing of B, has about half as much error as B. Log B errors in the upper part of the hole, where the formation had been longest exposed to mud, are around 5 or 6 percent; as the depth increases and the exposure to mud is less, the error approaches zero. This plot of error distribution versus depth is typical; the large errors are usually in the shallow part of the hole. Log A shows a very similar error distribution, except that it is only half the magnitude of the error of Log B. We should also expect slightly less than half as much error from Log A because of the 4.3-ft transmitter-to-first-receiver spacing compared with 3.0 for Log B. This

* The long interval survey was chosen because it permitted more check points over a longer section of the hole than the conventional geophone survey. The long interval showed a consistent difference from the geophone survey of one percent, so it was calibrated to the geophone survey. This calibrated long interval survey is taken as the zero-error line of Figure 5.

improvement is not appreciable. Neither log had adequate spacing for the borehole conditions in this well.

MECHANISM OF ALTERATION OF SHALE VELOCITY

When a well is drilled, the formations through which the bit passes are subjected to harsh treatment. The formation most likely to be altered is shale. It lacks the competence to withstand the mechanical and electrochemical stresses which follow penetration by the bit. First, formations immediately adjacent the well bore are subjected to a devastating upheaval of the mechanical stresses under which they had been resting. Previously, there had been a framework of rock grains supporting the overburden and a system of fluid-filled pores under some smaller hydrostatic pressure. Now, the mud column is introduced with pressure intermediate the grain pressure and the pore-fluid pressure. Under these circumstances, fluids from the well bore tend to displace fluids in the pores of permeable formations. This process is known as invasion. However, shales are generally so impervious that invasion caused by pressure differences is negligible. Water is imbibed from the drilling fluids. Sodium montmorillonite, a clay mineral, is especially sensitive to hydration by fresh water. Its lattice structure can expand tenfold in the presence of fresh water (Foster, Savins, and Waite, 1955) simply by expanding the lattice platelets and filling the intervening space with water. Experimental data have shown that clay samples, restrained in a pressure bomb, developed swelling pressures from 2,000 to 4,000 lb/in^2 when permitted to imbibe water (Power, Towle, and Plaza, 1942). This swelling pressure opposes overburden pressure, so for a given well one would expect manifestations of shale damage to be more pronounced in shallow depths. This is in agreement with the experimental data of Figure 5, which shows large errors in the shallow section of the well, gradually decreasing to zero near total depth.

Weaver (1958), in his studies of the clay mineral suites of the Pennsylvanian of the Anadarko Basin, observed that sodium montmorillonite is particularly abundant in the Springer section. Shale damage has been observed in the Springer shales, even at depths near 10,000 ft. Weaver also pointed out that the dominant clay type interspersed in pre-Mississippian carbonates is illite, so one would not expect shale damage in pre-Mississippian formations.

CALCULATIONS OF MINIMUM TRANSMITTER-TO-FIRST-RECEIVER SPACING

Certain assumptions are necessary to this calculation. They may be visualized by reference to Figure 6. A two-receiver logging tool is centralized in the hole. Transducer diameter is three inches. The first arrival from the transmitter to each receiver follows a minimum time path. Snell's law defines the sine of the angle of the refracted ray as:

$$\sin \alpha = \frac{V_m}{V_f}$$

where V_f is the speed of sound waves in the formations surrounding the well bore

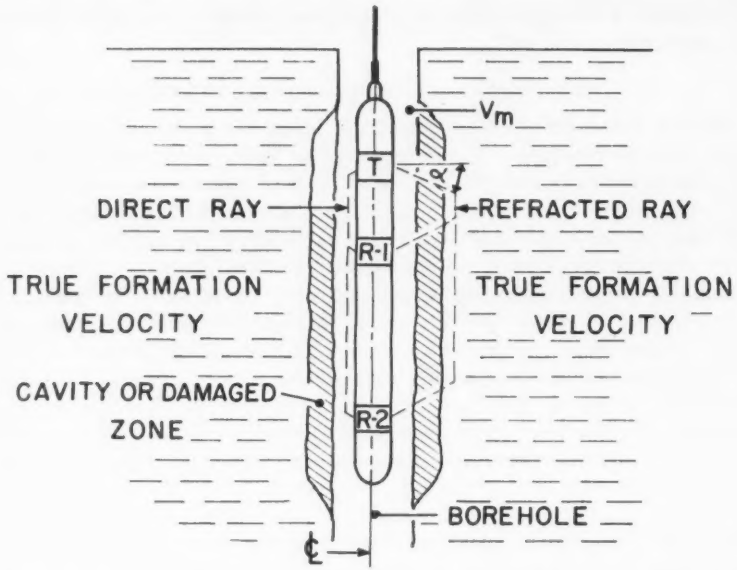

FIG. 6. Direct and refracted ray paths for a logging tool centered in a borehole. In this model, the speed of sound waves in a damaged shale is assumed to be the same as in drilling fluids.

and V_m is the speed of sound waves in the drilling mud. Assume then that the spacing between the receivers is 6 ft. Let the borehole wall be damaged shale and this damage have a variable diameter. Assume now that the damaged zone has the same velocity as drilling mud. In this model, damaged shale has the same effect as a cavity. The assumption that the damaged shale has the same velocity as drilling mud is oversimplified, but the basic argument remains the same. Actually, we would suppose that the speed of sound is low near the well bore and increases gradually until it reaches true formation velocity. The data of Figure 2 suggests that velocity increases as we proceed outward from the bore face. However, with this simplification we can make a qualitative comparison of the factors influencing the response of two-receiver tools. Observe that in this model the hole diameter is being effectively increased by shale damage. We shall define the acoustic hole diameter as the minimum cylinder which is surrounded by true formation velocity; it differs from physical hole diameter by the annulus of damaged shale.

Figure 7 illustrates errors incurred in velocity measurements in holes of large acoustic diameter for the above assumptions. Figure 7 is for formations of 8,000-ft-per-sec velocity. At the lower left-hand edge of the figure the line for 2-ft transmitter-to-first-receiver spacing has zero error for all diameters below 14 inches

and increases to 27 percent error at 30 inches. Similarly, the curve for 4-ft spacing shows zero error out to 26 inches and increases to 28 percent at 42 inches. The curve labelled "3-ft Detector Spacing" is plotted for all conditions remaining the same, except that the receiver span is changed from 6 ft to 3 ft. It has the same maximum diameter for zero error, but the slope is doubled compared to the 6-ft spacing. This tends to confirm the data of Figure 5, where we found twice as much error from a 3-ft receiver span as from the 6-ft span.

Figure 8 illustrates error conditions in 12,000-ft-per-sec formations. The points where the curve for a given transmitter-to-first-receiver distance departs from the zero error line are at larger acoustic hole diameters. For example, in using 6 ft between transmitter and first receiver on Figure 7, there is no error for hole diameters out to 38 inches. For the same conditions in Figure 8, there is no error

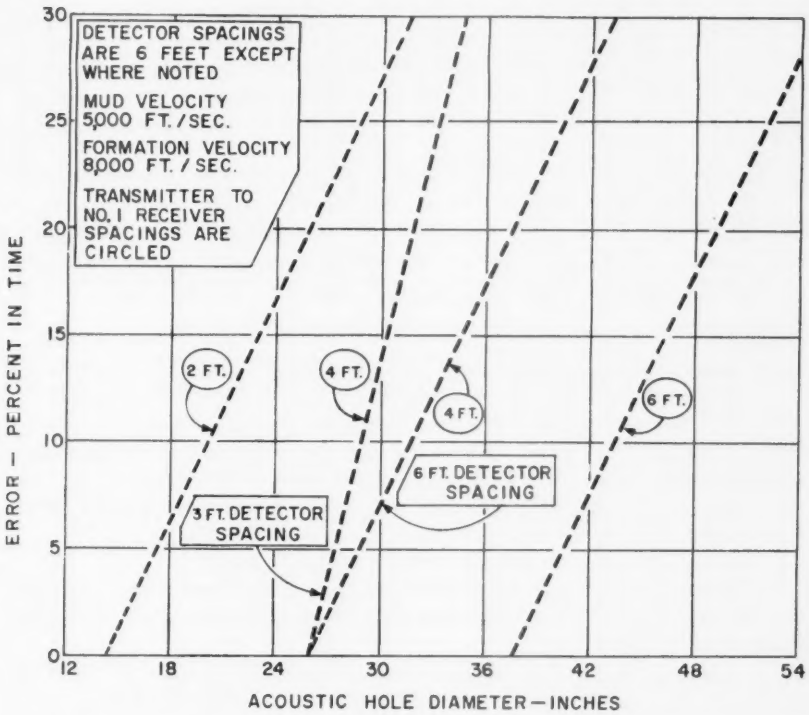

FIG. 7. Percent error in time measurements in holes of large acoustic diameter for 8,000 ft per sec formation. Longer transmitter-to-first-receiver spacings decrease log sensitivity to acoustic hole diameters. Also, in holes of large acoustic diameter, a log with 3-ft spacing between detectors has twice the error of one with 6 ft.

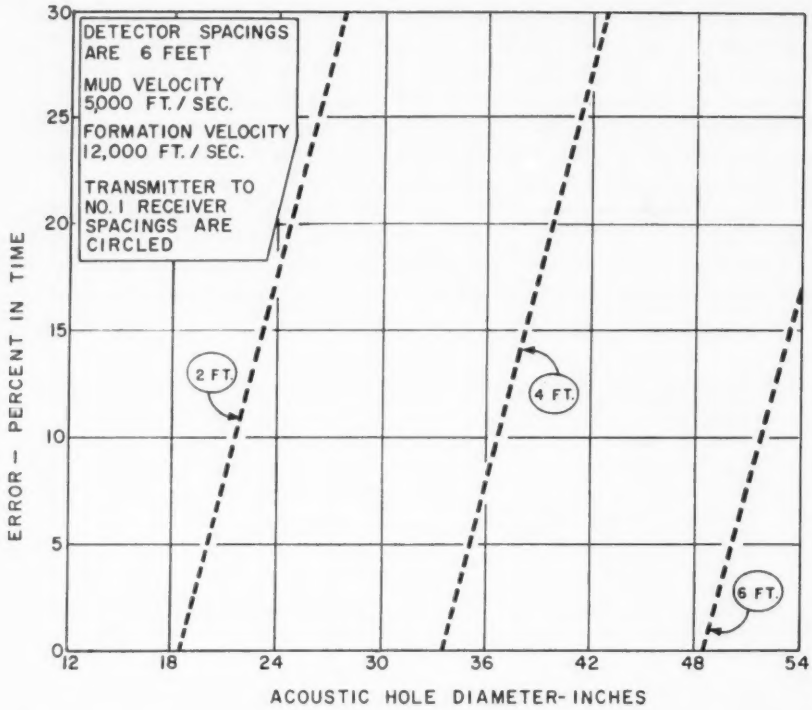

FIG. 8. Percent error in time measurements in holes of large acoustic diameter for 12,000 ft per sec formation. In higher velocity formations, hole diameters are larger before any error appears.

out to 49 inches. This is in accord with our field observations, which indicate that shale damage is not severe in hard rock country. However, the slopes of the lines in Figure 8 are steeper, so if extremely large acoustic hole diameters should be encountered in higher velocity formations, errors accumulate more rapidly.

Three important points arise concerning Figures 7 and 8:

1. All errors of this type are in the direction to make travel times read from the log greater than true travel times determined by geophone surveys or by longer spacing logs.

2. We rarely see physical hole diameters on caliper logs greater than 18 to 24 inches. But we do observe velocity measurements which indicate that the acoustic hole diameter (Figures 2, 3, and 4) is 30 to 50 inches in some shales. This inevitably leads to the damaged shale hypothesis.

3. If the transmitter-to-first-receiver spacing of the tool is gradually de-

creased, the response to hole diameter approaches the characteristics of a single-receiver tool.

AREAL DISTRIBUTION OF SHALE DAMAGE

Although our studies of the effects of shale damage upon velocity have been confined to the Miocene shales in the Louisiana and Texas Gulf Coast areas, and to Pennsylvanian and Permian shales of Central Oklahoma, similar effects undoubtedly exist in many other areas. They have not been observed in wells where formations have been exposed to the drilling fluid less than 10 days or in wells drilled with salt mud. They can be most easily observed by running a series of logs, increasing the transmitter-to-first-receiver spacing, and holding constant the spacing between receivers.

On the basis of our data, shale damage seems to be a geometrical problem where the transmitter-to-first-receiver spacing is crucial. In order to take advantage of the great accuracy potential of the two-receiver log, this spacing must be long enough so that sound waves are refracted through virgin formations. Of course, some compromise must be reached between the shallow penetration of a short spacing and the weak signal that goes with long spacing.

ACKNOWLEDGMENTS

I wish to express my appreciation for contributions to this work from A. W. Musgrave, A. A. Stripling, and J. E. Berry, and to the management of the Magnolia Petroleum Company for permission to publish this paper.

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DISCUSSION*

J. A. BROOKS†

The requirement that integrated vertical times from a continuous velocity log check to within some small percent the vertical times computed from the observed travel times of a geophone survey in the same borehole is to me unreason-

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† Humble Oil & Refining Company, Houston, Texas.

able. Although we geophysicists know that there are inherent errors in the results of geophone surveys because of possible errors in weathering velocity corrections, datum velocity corrections, depth of shot corrections, and especially seismic travel-path assumptions, we have presumed the cumulative error in all but unusual surveys to be within the limits of accuracy of reflection seismograph interpretation. The usual seismic travel path assumption, particularly in areas of high velocity stringers or velocity inversions, can be very treacherous in the computation of vertical times. Consequently, I cannot understand why some of our colleagues insist that the log results are incorrect unless they check very closely with the computed vertical shot times. Maybe the computed times are wrong!

DISCUSSION**

E. KAARSBERG‡

The discrepancies between regular geophone-type logs or surveys and continuous velocity surveys have been noted ever since the latter came into use. Hick's speculations as to the cause of these discrepancies in terms of compositional and structural changes in the rock surrounding the borehole are, therefore, welcome. His description of the actual mechanism of alteration of shale velocity due to shale damage is, however, brief, and some additional and/or alternative causes, which could be considered, are given below.

For one thing, the borehole on penetrating the strata relieves the rock of a considerable amount of stress next to the hole. The effect of any stress system, which tends to reduce the volume of the material stressed, is generally to increase its elastic moduli. Such effects may prove to be insignificant by comparison with the "shale damage" or other effects, but until experimental proof to the contrary is produced, it should be considered. Bridgman, Frocht, and others have discussed the effects of such changes in stress distribution around holes or cavities in materials under stress.

A factor which is ignored, but which it seems could be important in these "shale damage" effects, is the decreasing porosity of shales with depth. In any case, a more detailed explanation than that which is given of the actual mechanism of "shale damage" as related to expanding montmorillonite clay lattices seems in order, particularly in view of the considerable literature now available on studies of clay minerals.

Although very little has been done in well-survey work to determine what clay minerals are present and how distributed in the section, it appears that in general the montmorillonite content decreases with increase in age of sedimentary rocks

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‡ Geophysical Service Inc., Dallas, Texas.

(Grim, 1953, p. 255–257). A logical reason, therefore, for the decrease in shale damage with depth, insofar as montmorillonite is the culprit, seems to be that the montmorillonite content decreases with depth.

Montmorillonites other than the Na^+ type occur, and insofar as drilling muds are usually made of bentonite composed of the clay mineral montmorillonite, carrying Na^+ as the exchangeable ion, the phenomenon of cation exchange seems to be one that is likely to occur. Again, Hicks has nothing to say about this interesting possibility and how it may contribute to the "shale damage" effect.

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AUTHOR'S REPLY TO MESSRS. KAARSBERG AND BROOKS

The comments by Messrs. Kaarsberg and Brooks are welcome, because they offer alternate explanations for effects noted in our field work. I shall discuss some of these points in greater detail.

REPLY TO DR. KAARSBERG

Paragraph II: Kaarsberg states that mechanical stress relief should not be ruled out as an explanation of low velocity adjacent the borehole. If the volume of the material stressed increases, the elastic moduli decrease. Therefore, velocity immediately adjacent the bore decreases. This is indeed a powerful point and properly should have been discussed more fully.

Stress relief in a given well increases with depth because geostatic pressure increases more rapidly than the hydrostatic head of the mud column. Therefore, if stress relief is an important factor, the greatest discrepancy between deep versus shallow penetration logs should occur at greatest depths. That this does not occur is evident from the data of Figure 5: The maximum alteration in velocity occurs in the shallow portion of the well. This pattern of error distribution versus depth is well established.

The paragraph on "Mechanism of Alteration of Shale Velocity" briefly suggests one process of alteration which is compatible with present knowledge of velocity measurements and with clay mineralogy. Laboratory proof of these ideas is hampered by the difficulty of recovering hydratable shale cores uncontaminated by drilling fluids. Even after cores are taken, the friability of some shales prevents satisfactory laboratory measurements of velocity. For this reason measurements have been made *in situ*, and the mechanism causing lateral velocity gradients in the vicinity of the well bore remains poorly defined.

Paragraph V: Cation exchange appears to be the key to the entire problem, and I appreciate the opportunity to discuss it at greater length. Sodium and calcium are common forms of montmorillonite and are also common exchangeable

ions in drilling fluids. Only in mud systems where Na^+ is the exchangeable ion have we observed shale damage. X-ray diffraction analyses of a few field samples indicate that sodium montmorillonite is the dominant clay in damaged shales. Samples from the same wells showing no shale damage are primarily calcium montmorillonite or illite. The two montmorillonites differ in that no observation of individual layers of calcium montmorillionite swelling to more than 19.6 angstroms is reported; sodium montmorillonite continues to swell until the swelling pressure is equalized by geostatic pressure. Present data suggest that there is a possibility of eliminating shale damage by using mud systems having one of the following: Ca^{++} as the exchangeable ion (calcium surfactant or T-8, Shale-Ban) or oil as the continuous phase (inverted emulsion or oil base) or salt saturation.

REPLY TO MR. BROOKS

I agree that we have too long considered geophone surveys sacred. However, if a true two-receiver log is run it should neither be sensitive to spacings nor to elapsed time since drilling. If, as in Figure 3, three logs are run yielding three different answers, at least two of them are incorrect. Inconsistencies among logs necessitate a standard check. The geophone survey is useful as a standard in measuring times over long intervals and has been of value in pointing out deficiencies in our logs. If logs are run which are insensitive to spacing, a valid argument exists for ignoring computed shot times which disagree with the log.

GEOPHYSICS, VOL. XXIV, NO. 3 (JULY, 1959), PP. 465–478, 7 FIGS.

THE USE OF CRACOVIAN COMPUTATION IN ESTIMATING THE REGIONAL GRAVITY*

ZBIGNIEW FAJKLEWICZ†

ABSTRACT

The author uses the method of least squares in cracovian form and second order polynomials for estimating the regional gravity field. Expressions yielding the regional field are obtained very rapidly by using the inverse cracovians of the coefficients as given in the present paper, and there is no need of electronic digital computers for the computation. The equivalent of the entire work done by a computer of this kind in constructing the formula of the regional field, when effected by this method, takes no more than 20 minutes. The method is exemplified by the treatment of two gravity anomalies from the territory of Poland. The author stresses the fact that electronic computers adapted to the use of cracovians and characterized by a very high versatility may be applied in the method.

INTRODUCTION

The use of least squares in estimating the character of the regional gravity originated in a paper by W. B. Agocs (1951). The ideas of Agocs were developed by S. M. Simpson (1954), who applied higher order polynomials. C. H. G. Oldham and D. B. Sutherland (1955) introduced the use of orthogonal polynomials. The first published account of the use of least squares to determine a gravity regional appears to be that of Numerov, who in effect removes a first order polynomial. More precisely, he assumes the regional to be of the form $a+bh+cx+dy$, where the surface Cartesian co-ordinates are x and y, h is the depth of water in a lake, and the constants a, b, c, d are determined by least squares (see B. Numerov, 1929).

The two latter papers give methods involving the use of electronic computers. It is the aim of the present paper to provide an application of the least squares method in cracovian form to the estimation of the regional gravity. Cracovians, a variant on matrices, do not appear to be much used outside of Poland. A brief account of their properties is given in section 3 of the paper by A. E. Scheidegger and P. L. Willmore (1957).

Cracovian computation yields the ultimate result very rapidly, and there is practically no necessity of resorting to electronic computers.

For approximating the regional gravity function (Δg_R), only second order polynomials are used, as the author considers that using higher order polynomials for this purpose may lead to incorrect mapping of the function Δg_R. This is a result of the fact that the higher the order of the polynomial, the better it is suited for mapping the distribution of the observed anomalies of the gravity together with its local extrema, which is highly undesirable in the present problem.

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THEORETICAL DISCUSSION

The regional effect as second order polynomial may be written in the following cracovian form (T. Kochmański, 1953):

$$\Delta g_R = \begin{Bmatrix} y^0 \\ y^1 \\ y^2 \end{Bmatrix} \begin{Bmatrix} a_{00} & a_{10} & a_{20} \\ a_{01} & a_{11} & 0 \\ a_{02} & 0 & 0 \end{Bmatrix} \begin{Bmatrix} x^0 \\ x^1 \\ x^2 \end{Bmatrix}, \tag{1}$$

wherein (x, y) are the co-ordinates of the observed gravity values, and $a_{00}, a_{10} \cdots a_{02}$ are the coefficients to be determined. The best approximation to the distribution of the observed gravity values (Δg) by the polynomial (1) is obtained when the difference

$$\Delta g - \Delta g_R = \Delta g_L, \tag{2}$$

wherein Δg_L denotes the residual gravity and fulfills the condition

$$\sum (\Delta g_{Ln})^2 = \text{minimum}. \tag{3}$$

Condition (3) may be expressed by normal equations which, in cracovian form, are written as follows:

$$\begin{Bmatrix} a_{20} \\ a_{02} \\ a_{11} \\ a_{10} \\ a_{01} \\ a_{00} \end{Bmatrix} \tau \begin{Bmatrix} \Sigma x^4 & \Sigma x^2y^2 & \Sigma x^3y & \Sigma x^3 & \Sigma x^2y & \Sigma x^2 \\ \Sigma x^2y^2 & \Sigma y^4 & \Sigma xy^3 & \Sigma xy^2 & \Sigma y^3 & \Sigma y^2 \\ \Sigma x^3y & \Sigma xy^3 & \Sigma x^2y^2 & \Sigma x^2y & \Sigma xy^2 & \Sigma xy \\ \Sigma x^3 & \Sigma xy^2 & \Sigma x^2y & \Sigma x^2 & \Sigma xy & \Sigma x \\ \Sigma x^2y & \Sigma y^3 & \Sigma xy^2 & \Sigma xy & \Sigma y^2 & \Sigma y \\ \Sigma x^2 & \Sigma y^2 & \Sigma xy & \Sigma x & \Sigma y & \Sigma x^0y^0 \end{Bmatrix} = \begin{Bmatrix} Gx^2 \\ Gy^2 \\ Gxy \\ Gx \\ Gy \\ G \end{Bmatrix}, \tag{4}$$

this being a system of equations in the unknowns $a_{00}, a_{01} \cdots a_{02}$, wherein the various $\sum x^i y^i$ are the elements of the cracovian of coefficients $\boldsymbol{W}$, and $G, Gx \cdots$ are those of the cracovian $\boldsymbol{L}$ of free terms, with G denoting $\sum \Delta g$ on the grid under consideration, and $Gx, Gy, Gxy \cdots$ the respective products of the co-ordinates and values of the observed gravity anomalies Δg. τ denotes the so-called unit cracovian.

Equations (4) are solved according to T. Kochmański (1953) by computing the inverse of the cracovian of coefficients $\boldsymbol{W}$. When the latter is known, the unknowns $a_{00}, a_{10} \cdots a_{02}$ are immediately obtained by the cracovian operation

$$\boldsymbol{a} = \boldsymbol{L} \cdot \boldsymbol{W}^{-1}. \tag{5}$$

The use of the general solution for calculating the unknowns, which involves knowledge of $\boldsymbol{W}^{-1}$, is of great advantage in the present case, since the inverse, together with the square grid for which it has been computed, may be used for removing the local anomalies from the gravity on the various portions of plan of the survey.

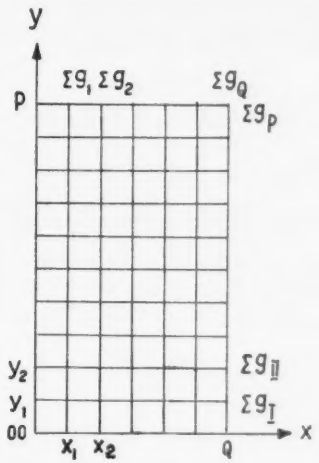

FIG. 1. Auxiliary graph determining the parameters in formulas (6)–(9). The symbols $\sum g_1, \sum g_2 \cdots \sum g_Q$ denote the sums of Δg in columns $x_1, x_2 \cdots x_Q$. For $y_1, y_2 \cdots y_P$ the sums are denoted by $\sum g_I, \sum g_{II} \cdots \sum g_P$.

COMPUTATION OF THE ELEMENTS OF THE CRACOVIAN OF COEFFICIENTS

Assuming that the points at which the measurements of the gravity anomaly are interpolated form a square grid of sides $x = y = 1$ over the rectangle $P(y) \times Q(x)$ the formulas for computing the elements of type $\sum \alpha^n$ of the cracovian of coefficients, in the reference system of Figure 1, take the form

$$\sum x^K = (P+1) \sum_{i=1}^{Q} x_i^K; \qquad \sum y^L = (Q+1) \sum_{i=1}^{P} y_i^L. \tag{6}$$

The elements of type $\sum \alpha^n \beta^m$ are easily obtained from

$$\sum x^K y^L = \sum^{Q} x^K \sum^{P} y^L. \tag{7}$$

The foregoing formulas resemble those in the paper by S. M. Simpson (1954); however, they assume a different shape, since the position of the square grid with relation to the co-ordinates is different here (more advantageous).

COMPUTATION OF THE ELEMENTS OF THE CRACOVIAN OF FREE TERMS

Retaining the assumption that the measurements of the gravity anomaly have been made at the points of a square grid covering a rectangle, the formulas for computing the elements of type $\sum g\alpha^n$ of the cracovian L, in the reference system used here, are of the form

$$\sum_{1}^{Q} Gx^{p} = x_1^p \sum g_1 + x_2^p \sum g_2 + x_3^p \sum g_3 + + + Q^p \sum g_Q, \tag{8}$$

$$\sum_{1}^{P} Gy^{q} = y_1^q \sum g_1 + y_2^q \sum g_{II} + y_3^q \sum g_{III} + + + P^q \sum g_P. \tag{9}$$

The notation is that of Figure 1.

COMPUTATION OF THE INVERSE OF THE CRACOVIAN OF COEFFICIENTS

If the cracovian $\boldsymbol{W}$ is symmetrical, its inverse is easily found by the operation of taking the root, according to the formalism of cracovian computation.

Denoting by $\boldsymbol{r}$ the (cracovian) square root of the cracovian of coefficients $\boldsymbol{W}$,

$$\boldsymbol{r} = \sqrt{\boldsymbol{W}}; \tag{10}$$

and denoting its inverse by $\boldsymbol{q}$

$$\boldsymbol{r}^{-1} = \boldsymbol{q},$$

we have

$$\boldsymbol{W}^{-1} = \boldsymbol{q}^2. \tag{11}$$

APPLICATION

Equations (6) and (7) were used for computing the cracovians of coefficients, and subsequently equation (11) for obtaining their inverses, for second order polynomials and a square grid over the following rectangles:

$P = 10$	$P = 15$	$P = 20$	$P = 15$	$P = 20$	$P = 20$
$Q = 10$	$Q = 10$	$Q = 10$	$Q = 15$	$Q = 15$	$Q = 20.$

The inverses are given by the Tables I-VI.

With the inverses as given above, the formulas describing the distribution of the regional effect within six areas of various sizes of the gravimetric plan of survey are easily obtained.

The construction of the formula yielding the distribution and values of the regional effect within an area considered, if the latter is bounded by one of the rectangles for which the inverses have been computed, reduces to the operation of equation (5). That is to say, if $\mathrm{I}_W{}^{-1}$, $\mathrm{II}_W{}^{-1} \cdots$ denote the various columns of elements in the respective inverse, then the unknowns a_{20}, a_{02}, $a_{11} \cdots$ are rapidly obtained by forming the following sums of products:

$$\boldsymbol{L} \cdot \boldsymbol{I}_W{}^{-1} = a_{20}; \qquad \boldsymbol{L} \cdot \mathrm{II}_W{}^{-1} = a_{02}; \cdots$$

The last column of the inverse, denoted by S, is also of use in checking the numerical values of the coefficients a_{20}, $a_{02} \cdots$, since the sum of the unknown coefficients and the cracovians $\boldsymbol{S}$ and $\boldsymbol{L}$ are related as follows:

$$\sum a_{ij} = \boldsymbol{S} \cdot \boldsymbol{L}. \tag{12}$$

TABLE I

Inverse of **W** for $P=10$, $Q=10$

I	II	III	IV	V	VI	S
0.000 105 956 010	0.000 000 000 370	0.000 000 000 590	−0.001 059 564 400	−0.000 000 006 700	0.001 589 358 000	0.000 635 743 870
0.000 000 000 370	0.000 105 952 440	0.000 000 000 240	−0.000 000 008 500	−0.001 059 525 800	0.001 589 309 000	0.000 635 727 750
0.000 000 000 590	0.000 000 000 240	0.000 082 645 450	−0.000 413 235 900	−0.000 413 230 800	0.002 066 153.000	0.001 322 332 580
−0.001 059 564 400	−0.000 000 008 500	−0.000 413 235 900	0.013 488 328 000	0.002 066 243 000	−0.030 356 680 000	−0.016 274 917 800
−0.000 000 006 700	−0.001 059 525 800	−0.000 413 230 800	0.002 066 243 000	0.013 487 853 000	−0.030 356 070 000	−0.016 274 737 300
0.001 589 358 000	0.001 589 309 000	0.002 066 153 000	−0.030 356 680 000	−0.030 356 070 000	0.148 920 500 000	0.093 452 570 000

TABLE II

Inverse of **W** for $P=15$, $Q=10$

I	II	III	IV	V	VI	S
0.000 072 840 455	0.000 000 000 144	0.000 000 001 044	−0.000 728 413 340	−0.000 000 008 320	0.001 092 665 700	0.000 437 085 683
0.000 000 000 144	0.000 015 914 144	−0.000 000 000 636	0.000 000 003 670	−0.000 238 708 160	0.000 556 964 600	0.000 334 173 762
0.000 000 001 044	−0.000 000 000 636	0.000 026 737 768	−0.000 200 544 660	−0.000 133 678 900	0.001 002 663 300	0.000 695 177 916
−0.000 728 413 340	0.000 000 003 670	−0.000 200 544 660	0.009 356 416 200	0.001 002 672 600	−0.021 287 584 000	−0.011 857 449 530
−0.000 000 008 320	−0.000 238 708 160	−0.000 133 678 900	0.001 002 672 600	0.004 516 382 000	−0.015 373 108 000	−0.010 226 448 780
0.001 092 665 700	0.000 556 964 600	0.001 002 663 300	−0.021 287 584 000	−0.015 373 108 000	0.108 410 170 000	0.074 401 771 600

TABLE III

Inverse of **W** for $P=20$, $Q=10$

I	II	III	IV	V	VI	S
0.000 043 444 730	0.000 000 000 140	0.000 000 000 220	−0.000 434 450 900	−0.000 000 004 800	0.000 651 706 000	0.000 260 695 390
0.000 000 000 140	0.000 004 052 630	0.000 000 000 250	−0.000 000 003 800	−0.000 081 054 100	0.000 256 683 000	0.000 179 678 120
0.000 000 000 220	0.000 000 000 250	0.000 011 806 640	−0.000 118 068 900	−0.000 059 038 500	0.000 590 356 000	0.000 425 055 710
−0.000 434 450 900	−0.000 000 003 800	−0.000 118 068 900	0.005 958 115 000	0.000 590 435 000	−0.014 585 160 000	−0.008 589 133 600
−0.000 000 004 800	−0.000 081 054 100	−0.000 059 038 500	0.000 590 435 000	0.002 034 342 000	−0.009 266 110 000	−0.006 781 430 400
0.000 651 706 000	0.000 256 683 000	0.000 590 356 000	−0.014 585 160 000	−0.009 266 110 000	0.082 508 500 000	0.060 155 975 000

TABLE IV

Inverse of **W** for $P=15$, $Q=15$

I	II	III	IV	V	VI	S
0.000 010 941 843	−0.000 000 007 298	−0.000 000 000 017	−0.000 164 127 760	0.000 000 109 330	0.000 382 707 800	0.000 229 623 898
−0.000 000 007 298	0.000 010 941 456	0.000 000 000 014	0.000 000 108 850	−0.000 164 121 910	0.000 382 696 600	0.000 229 617 712
−0.000 000 000 017	0.000 000 000 014	0.000 008 645 979	−0.000 064 844 740	−0.000 064 845 150	0.000 486 336 100	0.000 365 292 186
−0.000 164 127 760	0.000 000 108 850	−0.000 064 844 740	0.003 132 081 800	0.000 484 706 800	−0.010 766 848 000	−0.007 378 923 050
0.000 000 109 330	−0.000 164 121 910	−0.000 064 845 150	0.000 484 706 800	0.003 131 990 700	−0.010 766 652 000	−0.007 378 812 230
0.000 382 707 800	0.000 382 696 600	0.000 486 336 100	−0.010 766 848 000	−0.010 766 652 000	0.078 731 870 000	0.058 450 110 500

TABLE V

Inverse of **W** for $P=20$, $Q=15$

I	II	III	IV	V	VI	S
0.000 008 336 371	0.000 000 000 021	0.000 000 000 002	−0.000 125 045 540	−0.000 000 000 340	0.000 291 772 200	0.000 175 062 714
0.000 000 000 021	0.000 002 786 117	−0.000 000 000 018	−0.000 000 000 020	−0.000 055 722 380	0.000 176 454 400	0.000 123 518 120
0.000 000 000 002	−0.000 000 000 018	0.000 003 819 719	−0.000 038 197 110	−0.000 028 647 570	0.000 286 477 700	0.000 223 452 723
−0.000 125 045 540	−0.000 000 000 020	−0.000 038 197 110	0.002 397 708 000	0.000 286 479 000	−0.008 291 755 000	−0.005 770 810 670
−0.000 000 000 340	−0.000 055 722 380	−0.000 028 647 570	0.000 286 479 000	0.001 410 473 600	−0.006 489 360 000	−0.004 876 777 690
0.000 291 772 200	0.000 176 454 400	0.000 286 477 700	−0.008 291 755 000	−0.006 489 360 000	0.001 844 230 000	0.047 817 819 300

TABLE VI

Inverse of **W** for $P=20$, $Q=20$

I	II	III	IV	V	VI	S
0.000 002 122 756	0.000 000 000 072	0.000 000 000 030	−0.000 042 455 517	−0.000 000 001 775	0.000 134 449 970	0.000 094 115 536
0.000 000 000 072	0.000 002 122 637	−0.000 000 000 012	−0.000 000 001 365	−0.000 042 452 439	0.000 134 436 030	0.000 094 104 923
0.000 000 000 030	−0.000 000 000 012	0.000 001 686 631	−0.000 016 867 029	−0.000 016 866 017	0.000 168 664 540	0.000 136 618 143
−0.000 042 455 517	−0.000 000 001 365	−0.000 016 867 029	0.001 079 626 410	0.000 168 697 780	−0.004 994 095 800	−0.003 805 095 520
−0.000 000 001 775	−0.000 042 452 439	−0.000 016 866 017	0.000 168 697 780	0.001 079 547 940	−0.004 993 782 300	−0.003 804 856 811
0.000 134 449 970	0.000 134 436 030	0.000 168 664 540	−0.004 994 095 800	−0.004 993 782 300	0.048 532 122 000	0.038 981 794 440

Once the inverse of $\boldsymbol{W}$ and the cracovian $\boldsymbol{L}$ have been obtained, the computations necessary for the derivation of the formula accounting for the regional effect take no more than 20 minutes and involve no other instrument than a manual arithmometer.

EXAMPLES

The method is exemplified by the estimation of two gravimetric anomalies from the territory of Poland.

The first of these, known as the gravimetric anomaly of the vicinity of Poznań, is shown in Figure 2. Figures 3 and 4 show the result obtained by applying cracovian counting to construct the formula for Δg_R for the region under consideration.

The formula is the following:

$$\Delta g_R = +0.028x^2 - 0.029y^2 - 0.082xy + 0.576x + 0.483y + 4.208. \quad (13)$$

The result in Figures 3 and 4 have been checked and confirmed by those obtained by applying known methods to the same data.

Figure 5 shows the gravimetric survey of the vicinity of Suwałki. In this case, cracovian computation yields the following formula of the regional effect:

$$\Delta g_R = -0.098x^2 - 0.024y^2 - 0.072xy + 1.436x + 0.703y + 17.761. \quad (14)$$

The results are shown in Figures 6 and 7. The map of the regional effect is of special interest, showing a subterranean ridge to exist in the SE-NW direction; the existence of the south-eastern portion of the latter, beyond the frontier of Poland, was proved by borings effected there. This is the first time an exact gravimetric proof of its continuation into Polish territory is given. In this region, the application of other methods used for estimating the regional gravity had not lead to such a conclusion because of the exceedingly strong influence of the local element and the proximity of other important anomalies and also the frontier line.

CONCLUSIONS

The present paper confirms the basic idea of W. B. Agocs, S. M. Simpson, and C. H. G. Oldham and D. B. Sutherland on the usefulness of polynomials and least squares computation in estimating the regional gravity. The author is convinced that the use of cracovians for the same purpose presents very real advantages because of the possibility of obtaining the inverses of $\boldsymbol{W}$ rapidly and easily, without using an electronic computer. Once the tables of the inverses and the cracovian $\boldsymbol{L}$ are available, the computations leading up to the regional gravity formula take no more than 20 minutes. An easy and rapid method of checking the numerical values of the coefficients is given in equation (12). Inverses for the construction of formulas for the regional effect, computed on the assumption that the regional field may be expressed by second order polynomial curves, are

(*Text continued on page 476*)

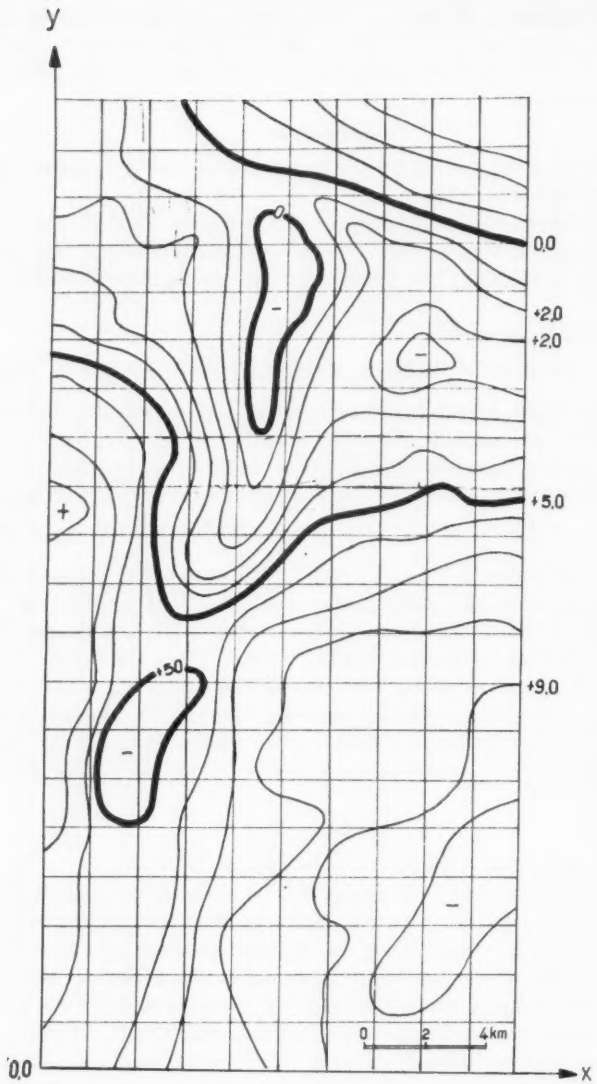

FIG. 2. The field of observed gravity anomalies of the vicinity of Poznań, according to Bouguer, prepared by W. Duda (PPG). Property of the Geological Institute, Poland.

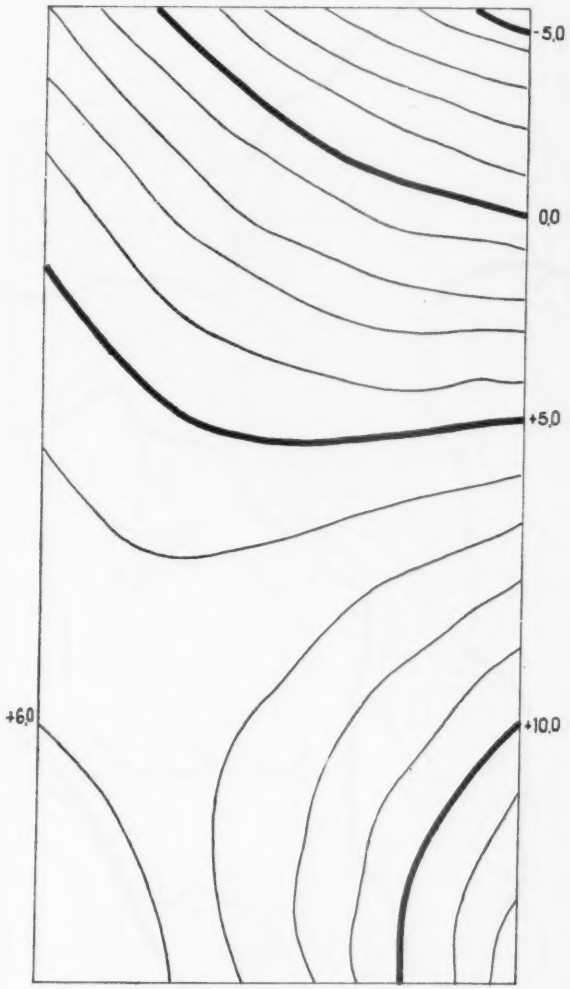

FIG. 3. Regional gravity as a system of second order polynomial curves, vicinity of Poznań.

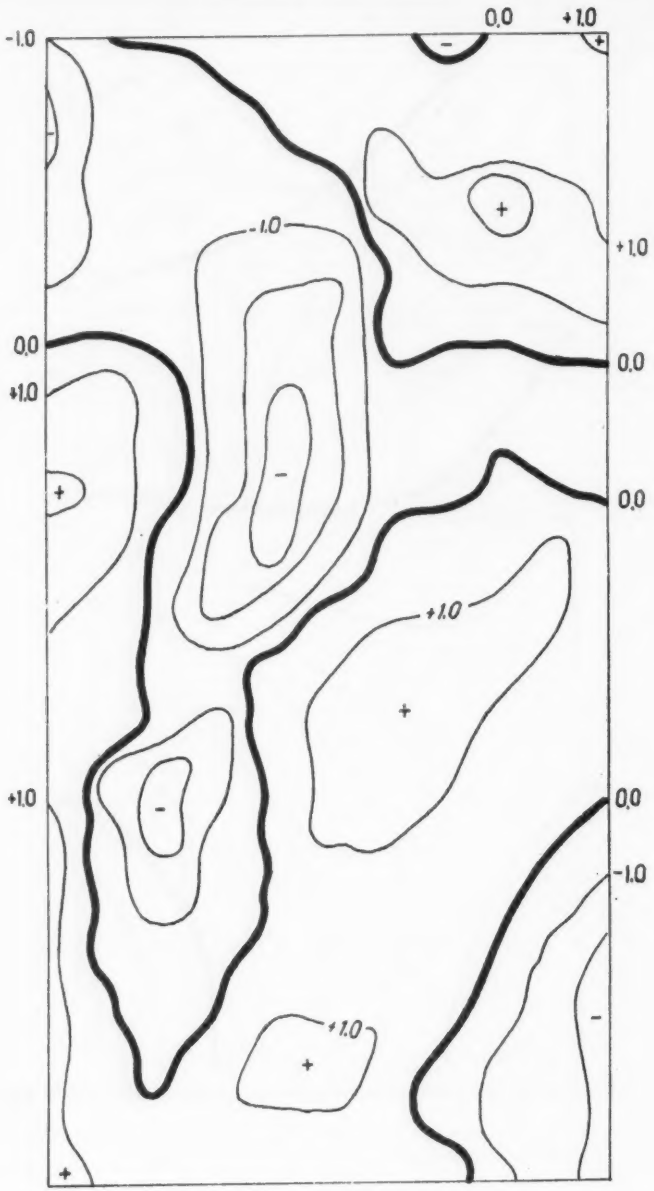

FIG. 4. Residual gravity, vicinity of Poznań.

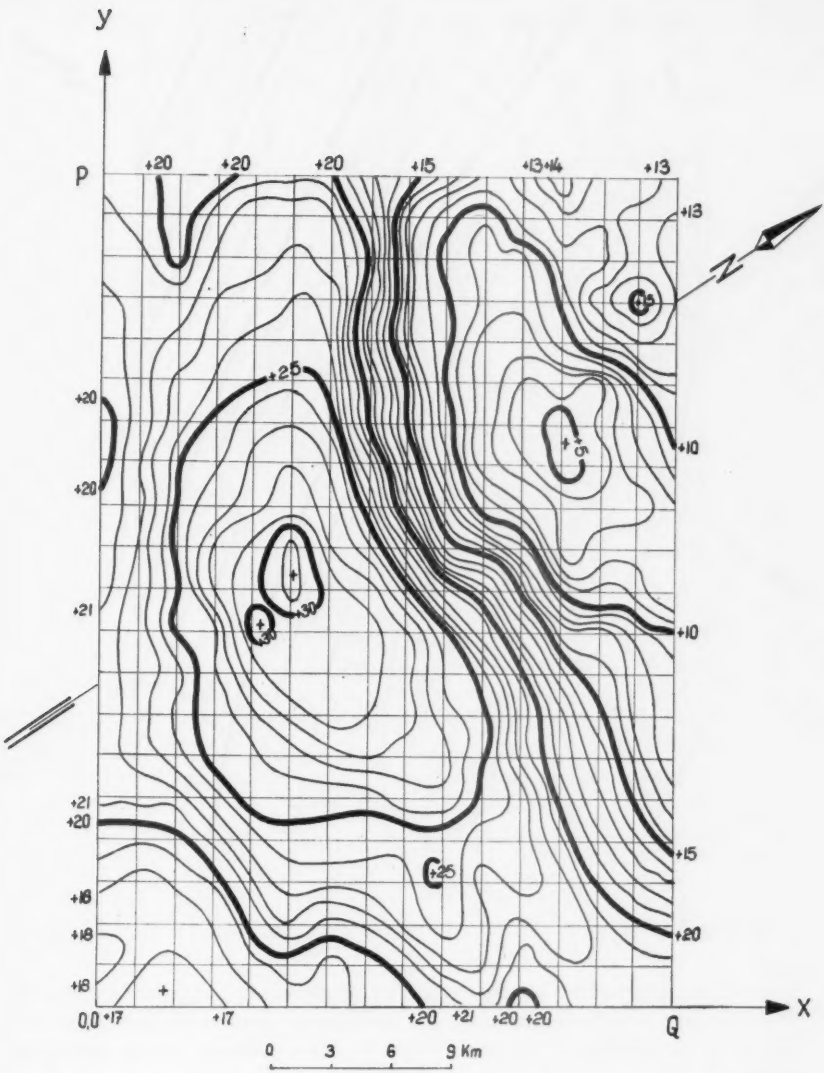

FIG. 5. The field of observed gravity anomalies of the vicinity of Suwałki, according to Bouguer, prepared by St. Reczek (PPG). Property of the Geological Institute, Poland.

FIG. 6. Regional gravity as a system of second order polynomial curves, vicinity of Suwałki.

given. It is noteworthy that the versatility of electronic computers adapted to the respective cracovian operations has been found to exceed many times that of the usual electronic computers, especially those used in typical geodetical work.

ACKNOWLEDGMENT

The author is indebted to Dr. T. Kochmański for his valuable aid in computing the inverses.

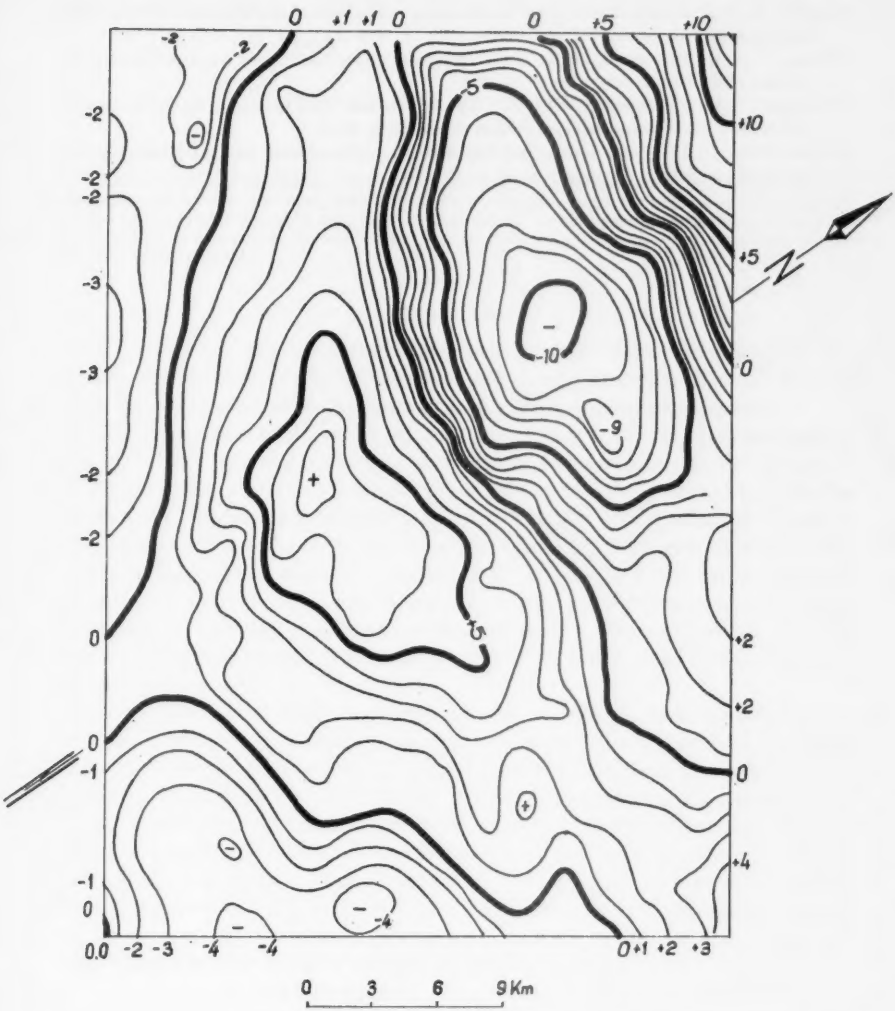

FIG. 7. Residual gravity, vicinity of Suwałki.

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GEOPHYSICS, VOL. XXIV, NO. 3 (JULY, 1959), PP. 479–484, 1 FIG.

STANDARDIZATION OF GRAVITY SURVEY PROCEDURES*

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ABSTRACT

Standardization of gravity datum, gravity meter calibration, latitude correction, elevation datum, average density correction factor, map scale and grid, and gravity bench mark information between companies working in the same area prior to execution of the surveys is recommended to facilitate future trades of information. Governmental agencies, geodesists, and earth scientists will also benefit by such standardization.

INTRODUCTION

A great many gravity surveys have been made and are being made by industry, not only within but also outside the United States. Gravity data from all over the world are now in the possession of a large number of companies.

The importance of the results of these gravity surveys is far more encompassing than their primary purpose of prospecting for minerals and oil. George P. Woollard (1958) enumerates various other aspects of gravity exploration besides prospecting. These are determinations of undulations of the geoid, deviation of the vertical, crustal structure, local geology, crustal strength and rigidity, thickness of polar ice caps, and ice movement. All these can be derived from observed gravity values. Although some of the above mentioned applications of gravity data may be regarded as only of academic interest by the explorer for minerals and hydrocarbons, several of them may give results which are of direct or indirect use to industry.

Extensive and voluntary co-operation between industry, government agencies, and pure scientists to achieve standardization is highly desirable. Such co-operation, which nearly always involves an exchange of data among interested parties, will be greatly facilitated if the data are on a comparable basis. Geodesists and other scientists can use such standardized gravity data directly without wasting scientific manpower for laborious recomputation. Having the data on a comparable basis is of as great importance within industry itself in view of the many trades of data which are taking place, more so abroad than domestically because of the differing land situation. The cost of countless hours of recomputing and map making can be saved if we can standardize certain elements of our gravity exploration. Individual surveys may also profit as a result of elimination or reduction of costly topographic and gravity ties if a proper exchange and standardization agreement can be made between several companies operating in the same general area prior to execution of the gravity surveys.

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PROCEDURE

The elements to be standardized are:

1) datum for observed gravity,
2) gravity meter calibration,
3) the latitude correction,
4) datum for elevations,
5) density correction factor,
6) map scale and grid,
7) use of the metric system where feasible,
8) gravity bench mark information.

1. *Datum*

Since Woollard and others (1952) have established a world-wide network of gravity bases, it is usually possible to tie a gravity survey to one of their stations. The observed gravity values can thus be made absolute, instead of being based on an assumed value at some central point within the project area. The widespread use of the airplane and the helicopter in industry facilitates the making of these ties to the world-wide network. When properly scheduled to coincide with the needs for transportation of personnel or equipment, these gravity ties could be made with a nominal or moderate expense. The geophysicist also will be aided materially in his interpretation by the knowledge that the data are on the absolute gravity datum.

2. *Calibration*

Nearly all companies using gravity meters have their own calibration test runs during which the gravity meter constant is determined. After determination of the meter constant, the instrument is shipped to the project area and a local calibration test range established for periodical checks of the instruments in use in that area. Woollard et al. have often observed several stations near one of the key stations of their world-wide network. Such stations can also be used for the calibration of the gravity meters in those areas if the observed gravity difference between the stations is large enough to make negligible the lesser accuracy of the geodetic type gravity meters used in establishing the network. In the absence of such base stations, the gravity meters can be calibrated between any two base points with sufficiently large gravity difference. This gravity difference should be computed from measurements with several factory calibrated gravity meters, and the computed value should be accepted for calibration by the surveying companies. If all gravity meters of different companies have been calibrated on the same range, their results will be directly comparable. Gravity bench marks set by one instrument can then be used by all instruments without more than the allowable misclosure.

3. *Latitude Corrections*

As this is already generally the practice in the industry, latitude corrections should be based on the 1930 "International Formula" (Nettleton, 1940). Linear (per mile, or per kilometer) latitude corrections should be eliminated, and a true grid should be used corresponding to the International Formula and drawn to the scale and projection of the maps used in the specific area.

4. *Elevation Datum*

Sea level is the most reasonable and most widely accepted reference datum for elevations. A reasonably reliable elevation with respect to sea level can usually be obtained at railroad stations and airports in the less developed countries. However, even these may not be available in the less inhabited parts of the world. In that case, an altimeter tie should be obtained concurrent with the gravity tie to one of the bases of the world-wide gravity network. While on this subject, we would like to point out that a contoured station elevation map should form an intrinsic part of an exchange of gravity information. Such a map will afford a quick check (admittedly less reliable than a density profile) of the appropriateness of the density correction factor used, as well as bring out any structurally significant correlation between surface topography and the Bouguer anomaly.

5. *Density Correction Factor*

For obvious reasons, standardization of the density correction factor is theoretically impossible. Local surface density determinations can be made by the execution of density profiles, or by adopting average densities of the rock type forming the topography. Elevation corrections with these locally determined density values should be made only to a datum surface drawn through the lowest points of the topography, as suggested by Vajk (1956). Corrections for the elevations between this datum surface and sea level should be computed by using a standard density. This standard density should be agreed upon by the surveying companies. The density value 2.67 used by geodesists in making the Bouguer corrections for isostatic reductions seems unacceptable in sedimentary basins. A more realistic value, close to the average density of the sedimentary fill in the particular basin may be adopted.

The question may be raised now: how to draw a curve, or rather a surface through the low points of the topography?

The simplest way is to do it graphically. The following procedure is suggested.

1. Contour the elevation data.
2. Construct elevation profiles from this contour map along the lines where the gravity stations were made.
3. Draw a line as smooth as possible through the low points of the elevation profiles (see Fig. 1).

4. Using the curves described in 3, construct an elevation contour map of the surface through the low points of the topography.
5. The elevations (h_1) of the surface drawn through the low points of topography at the gravity stations can be read from the contour map described in 4.
6. We may write now $H-h_1=h_2$, where H is the elevation of the gravity station. The total Bouguer correction will be:

$$\Delta g_2 = -0.0419(h_1\sigma_1 + h_2\sigma_x) \text{ milligal}$$

where h_1 and h_2 are in meters and σ_x is the local surface density, while σ_1 is the density used all over the particular region for the rocks between the low points of the topography and the sea level.

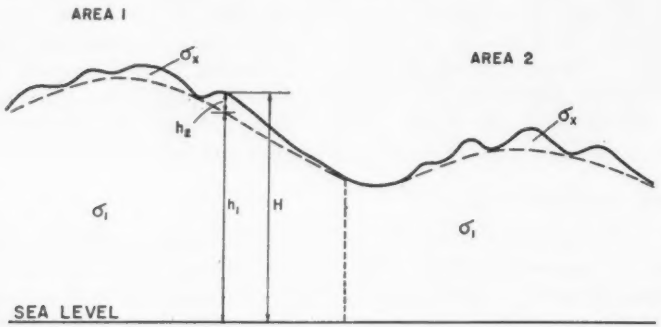

FIG. 1. This sketch presents an example for drawing a smooth line through the low points of the topography. Bouguer corrections for the rocks above this smooth line should be computed with the density of the local surface rocks, and Bouguer corrections below this line should be computed with the same (constant) density throughout the entire survey.

The objection may be made that drawing a smooth curve through the low points of the topography is subject to a personal factor. This is true, but drawing an isogam map on the observed gravity values, or drawing a geological map, or a geological profile on a finite number of observations is also subject to the very same personal factor. However, the following two arguments may be mentioned to support the above described graphical method:

1. Variations in drawing the line through the low points of the topography do not result in serious errors. If $|\sigma_1-\sigma_x|=0.25$, a 10 meter error, if $|\sigma_1-\sigma_x|=0.1$, a 23 meter error in drawing the smooth curve will cause an error of only 0.1 milligal in the computed Bouguer correction.
2. Only the h_1 elevation values at the border between the two areas, the gravity surveys of which are to be connected, are considered when con-

necting the two gravity surveys. The manner in which the smooth elevation curves are drawn through the low points of the topography within an area affects only the Bouguer corrections within that particular area.

In case a rigid mathematical procedure is favored for constructing a surface through the low points of the topography, these points may be tabulated and by the use of an electronic computer a suitable geometrical surface may be computed. This computed surface will then be contoured and the procedure described above in 5 and 6 may be followed.

If the above procedure is followed, adjoining gravity surveys can be directly integrated even if a different surface density has to be used in each individual survey. Early execution of density profiles by several companies having concessions covering a large area is strongly recommended to implement the procedure set forth above.

6. *Map Scale*

In many foreign countries commercial facilities for reproduction and reduction of maps are inadequate. It therefore behooves the companies who visualize future exchanges of gravity data to agree at an early stage on the map projection and scales to be used. A map scale of 1:100,000 is almost universally acceptable. We suggest further that the maps at a scale of 1:100,000 be established on quadrangle sheets measuring one degree of geographical latitude by one degree of longitude, or if a smaller physical size is desired, one-half by one-half degree. This will facilitate assembly of the regional map as well as map indexing.

7. *Metric System*

Excepting in those countries where non-metric systems are used throughout, we strongly recommend the adoption of the metric system for gravity and topographic computations and measurements.

8. *Bench Marks*

Permanent gravity bench marks should be erected on grid intersections near concession boundaries. The following information should be made available in an exchange of data concerning these gravity bench marks:

a) designation of station,
b) date set,
c) geographical location,
d) location with respect to landmarks and accessibility,
e) elevation,
f) observed gravity value,
g) density correction factor used,
h) Bouguer anomaly,
i) any other information helpful and pertinent.

Conclusion

The standardization principles outlined above are considered in accordance with good operating practice. Except for the elevation correction procedure, they have been applied by nearly all companies operating in at least one foreign country and are regarded as satisfactory. We therefore recommend them for adoption by the entire industry.

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GEOPHYSICS, VOL. XXIV, NO. 3 (JULY, 1959), PP. 485–509, 2 FIGS.

AN IMAGE ANALYSIS OF MULTIPLE-LAYER RESISTIVITY PROBLEMS*

IRWIN ROMAN†

ABSTRACT

The Kelvin method of images is expressible by a transflection at a boundary. The original source is augmented by a supplement and a complement. The supplement contributes to the potential on the same side of the boundary as the source, but it lies at the optical image position of the source in the boundary. The complement lies at the position of the source but contributes to the potential on the opposite side of the boundary.

For two or more boundaries, there are two exterior regions and one or more interior regions. For a source in the top layer, a primary sequence starts with a downward transflection and a secondary sequence with an upward transflection. To each primary sequence of transflections there corresponds a secondary sequence with an upward transflection at the upper boundary ahead of it. The exterior images are not transflected again. Successive transflections occur at adjacent boundaries, suggesting a link of two transflections. To a sequence of links, called a chain, there corresponds an associated sequence, obtained by dropping the last transflection.

Exterior images follow from interior, associated from chain, and secondary from primary. Thus, only primary, interior, chain images need to be traced.

Each potential is the sum of terms of the form m/r where m is the strength of a specific image, r is the distance of that image from the test point, and the sum includes all images contributing to that potential.

The addition of each boundary introduces images and potentials that must be added to those existing prior to the introduction, but it does not otherwise alter them.

For the three-boundary problem, the separate image strengths are determined by simple multiplication after a kernel polynomial is calculated. The latter is a finite polynomial in the reflection-factor at the middle boundary and can be tabulated. For the images of a specific potential and depth group, the strengths satisfy a recursion formula that serves as a check on direct evaluations.

INTRODUCTION

In 1845, Lord Kelvin (Sir William Thomson) introduced the term "electrical image" in discussing the attraction of two charged spheres. Since that time, numerous investigators have applied the method to problems of electrostatics and correlated problems of potential theory and current flow. In particular, Maxwell indicated the application of the method to plane, parallel boundaries. One of the principal advantages of the method is its freedom from the need of calculus and of familiarity with the more complicated problems of harmonic functions. On the other hand, only a relatively few problems have been solved by images and many apparently simple problems lead to contradictions such as prohibited internal images (Keller, 1953). Another disadvantage is that the simple set of images due to a single boundary is replaced by an infinite set of images when multiple boundaries are involved. For theoretical solutions and general conclusions Bessel functions are convenient, but for numerical evaluations they are difficult to apply, even when adequate tables and automatic computers are

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available. The terms of the series are relatively simple and the number can be determined by their behavior and the tolerances permissible for each problem.

In 1931, an analysis by the image method for the problem of two parallel boundaries was published (Roman, 1931) and tables for the geophysical case, in which the upper medium has an infinite resistivity and all measuring contacts are located on one of the boundary planes, were included. In 1933, an analysis appeared (Roman, 1933) for the problem of three parallel boundaries. Both of these solutions were algebraic and consisted essentially of isolating one term of an infinite series to satisfy the boundary conditions when associated with terms previously calculated. The present paper presents a direct symbolic attack on the problem and applies the method to each of the cases previously considered.

Although no numerical examples are included, the needs of the computer have been emphasized, and the processes involved have been stressed to permit extension to more complicated problems. Although the discussion uses infinite series, many of the series terminate automatically and hence are finite. The application becomes unwieldy unless the series converges or diverges in such a way that the convergent portion can be separated from a divergent portion which is independent of the location of the test point.

In the two-boundary problem, there are two lengths and three resistivities. For the geophysical case, one resistivity is infinite so that there are essentially only two. As units are arbitrary, one length and one resistivity may be taken as unity, leaving only one relative displacement of the test point from the pole and one relative resistivity of the bed referred to that of the overburden, the former being defined as the space below the second boundary and the latter as the space between the boundaries. For convenience, the relative resistivity is replaced by the reflection factor. This leads to a superposition method involving only twenty curves on double logarithmic paper (Roman, 1934) for a spacing of one-tenth in the reflection factor.

The three-boundary problem is more complicated. There are three lengths, one displacement and thickness of each of two layers. As only one of these can be selected arbitrarily, two lengths are needed. Likewise, for the geophysical case, there are three resistivities. As one resistivity can be selected arbitrarily, two reflection factors are needed. Thus, even for double logarithmic paper, numerous curves are needed. As an example, assume the upper layer resistivity as one. Then for a spacing of one-tenth in the reflection factors, there are 441 combinations. Of these, 41 may be omitted as due to zero values of one or both reflection factors. Analysis shows that the third boundary is ineffective if the lower layer is perfectly conducting or perfectly insulating with reference to the upper layer, eliminating 20 more curves. There are still 380 combinations of reflection factors to investigate numerically. Even the restrictions that the depth of the third boundary shall not exceed twelve and that the thicknesses of the two layers shall be relatively prime (i.e., have no common integral factor other than one) leaves 45 distinct combinations of thicknesses. For both assumptions jointly

17,100 curves would be needed. Although results may show that some of these are not needed, each would need calculation to learn how many curves such an album would need. The present study shows that auxiliary tables can be prepared and combined to permit curves to be computed as needed, using only a desk calculator.

GENERAL PROBLEM

Notation

Geometry. Let space (Figure 1) be divided into $(n+1)$ regions G_k, of resistivities ρ_k, where $0 \leqq k \leqq n$, by n horizontal planes B_k, where $1 \leqq k \leqq n$, whose depths below B_1 are d_k. By a simple rotation, every space divided by parallel planes can be reduced to that in which the planes are horizontal so that the assumption of horizontal planes involves no loss of generality. Let k increase downward, consecutively, so that the region G_{k-1} lies above the boundary B_k and the region G_k below it. Accordingly, the region G_k is separated from the region G_{k-1}, above it,

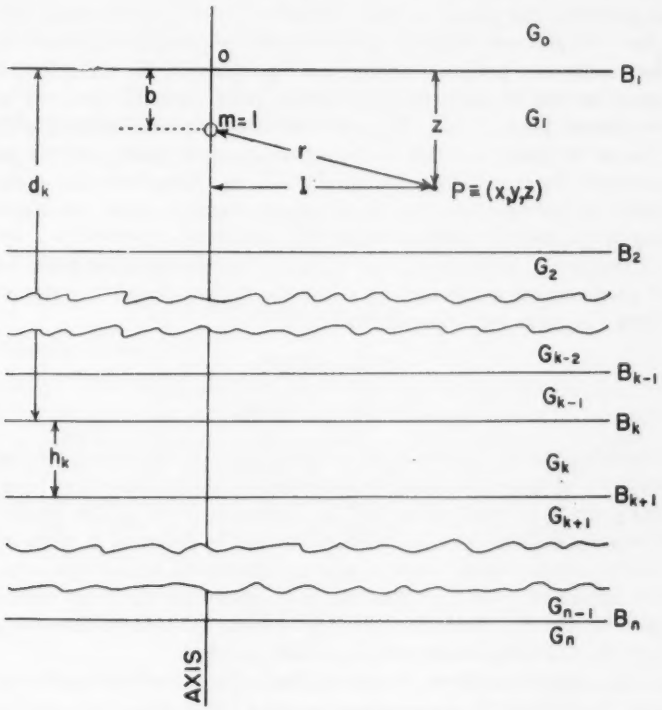

FIG. 1. Horizontal layering notation.

by the plane B_k and from the region G_{k+1}, below it, by the plane B_{k+1}. A point on a boundary of G_k is considered as the limiting position within G_k, as the point approaches the boundary.

In particular, each region extends indefinitely in every horizontal direction. G_0 extends indefinitely upward, and G_n extends indefinitely downward. Each region will have a constant resistivity so that it is electrically uniform (homogeneous and isotropic).

An interior region G_k has a thickness $h_k = d_{k+1} - d_k$, for $1 \leqq k \leqq n-1$. For the present analysis, the source is selected at a distance b below B_1, where $0 \leqq b \leqq h_1$. For other assumptions, similar analyses are possible (e.g., see Roman, 1959).

In the geophysical case, the upper region G_0 consists of air of infinite resistivity, the region G_n is designated as the "bed" of the earth, and the interior regions G_k $(1 \leqq k \leqq n-1)$ as "layers" or "overburdens." Also, in the geophysical case, b is taken as zero.

Co-ordinates. Let the z-axis extend vertically, positive down, through the current source. For the basic problem, there is one current pole, located at $(0, 0, b)$, and one potential test point, located arbitrarily at $P = (x, y, z)$, where the x- and y-axes lie in B_1 and are mutually perpendicular. In practical applications, there must be exactly two potential points, one for reference, the other for test, and there must be one or more positive current poles (sources) and one or more negative current poles (sinks). The potential at each potential point is the algebraic sum of the potentials due to the separate current poles, and the potential as measured is the excess of the potential at the test point over that at the reference point. Accordingly, only the basic problem needs analysis, the applications requiring only algebraic addition of the basic solutions.

As a matter of convenience, the "distance" of the potential point from the current pole may be designated by r and the "displacement" of the potential point from the z-axis by l. Specifically,

$$l^2 = x^2 + y^2, \tag{1.1}$$

$$r^2 = l^2 + (z - b)^2. \tag{1.2}$$

Potential Function. The potential function expresses the value of the potential at every point of space and satisfies established conditions that have been known for many years (e.g., see Roman, 1931, p. 2; Roman, 1933, p. 129; Roman, 1951, p. 186; or standard treatises). In order to express the potential in terms of simple functions, it is convenient to use a separate expression U_k for the value of the potential applicable over the region G_k. The expression U_k is not valid outside the region G_k, but U_{k-1} and U_k approach the same value from either side of the boundary B_k, and all boundary conditions are satisfied.

In a homogeneous medium, the potential at a distance r from a pole of strength m is m/r. Accordingly, it is convenient to make the analysis for a unit pole and multiply the final results by m. For a current of strength I in a medium of resistivity ρ, the corresponding pole strength is $m = \rho I/(4\pi)$. The potential func-

tion contains an arbitrary term that is independent of the position of the test point. However, measured potentials always involve the difference between two values of the potential, and the constant term disappears.

Images. The Kelvin method of image (Thomson) states that each boundary may be replaced by a set of images properly selected. The images depend on the position of the current source, the position of the boundary, and the resistivities on each side of the boundary. The resistivity of all space becomes that of the medium containing the source.

If the images contributing to U_k have the strength $m_{k\omega}$ and are located at $(0, 0, z_{k\omega})$, the potentials at the test point $P=(x, y, z)$ have the values:

$$U_0 = \sum_{\omega} \frac{m_{0\omega}}{r_{0\omega}}, \tag{2.11}$$

$$U_1 = \frac{1}{r} + \sum_{\omega} \frac{m_{1\omega}}{r_{1\omega}}, \tag{2.12}$$

$$U_k = \sum_{\omega} \frac{m_{k\omega}}{r_{k\omega}} \qquad (2 \leqq k < \leqq n), \tag{2.13}$$

where r is given by equation (1.2) and

$$r_{k\omega}^2 = x^2 + y^2 + (z - z_{k\omega})^2. \tag{2.2}$$

The symbol ω represents the set of all counters other than k, and the summation covers all possible values of ω.

IMAGE TRACING

Single-Boundary Image

The images due to a single boundary form the basis of analysis for multiple boundaries. For this case, n (Figure 1) is one. The upper medium, of resistivity ρ_0, may be replaced by a medium of resistivity ρ_1 if the original unit pole, located in G_1, is augmented by two images, a complement $m_c = 1 - Q_1$ located at the position of the original pole, and a supplement $m_s = -Q_1$ located at the optical image position, in the boundary, of the original pole. The quantity Q_1 has the value

$$Q_1 = \frac{\rho_1 - \rho_0}{\rho_1 + \rho_0}. \tag{3.1}$$

The potential in G_k has the value

$$U_0 = \frac{1 - Q_1}{r}, \tag{3.21}$$

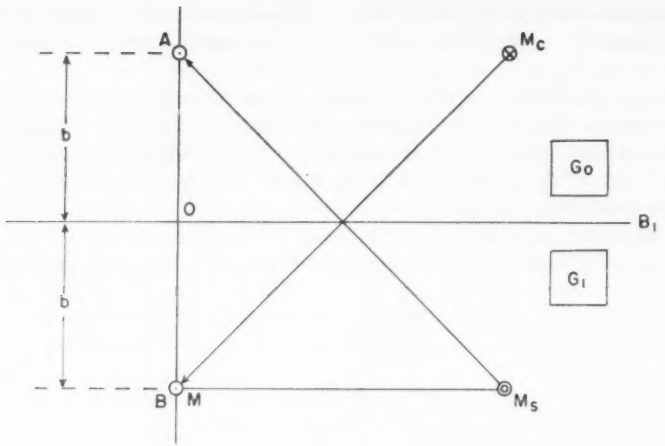

FIG. 2. Schematic single reflection:
m = current pole at $B = (0, 0, b)$,
m_s = supplementary image at $A = (0, 0, -b)$,
m_c = complementary image at $B = (0, 0, b)$.

$$U_1 = \frac{1}{r} - \frac{Q_1}{r_s}, \tag{3.22}$$

where r is given by equation (1.2) and

$$r_s^2 = l^2 + (z + b)^2. \tag{3.3}$$

Figure 2 represents the images schematically. Both images lie on the axis (the line through the source and perpendicular to the boundary), but the lateral displacement indicates a transflection. The complementary image contributes to U_0 and lies at B; the supplementary image contributes to U_1 and lies at A. The false positioning is convenient in tracing image sequences and permits consideration of the potentials rather than the image positions, which can be determined without difficulty.

The image method leads to positions determined as for optical reflection, and the term reflection factor has been used (Roman, 1931) for the quantity Q_1, or its negative. However, the strengths must be determined by the boundary conditions, and they do not follow the optical analog. The process of image creation may be called a "transflection." If the initiating pole or image is in G_k, the transflection may be upward at B_k or downward at B_{k+1}, producing a complement contributing to U_{k-1} or U_{k+1}, respectively, and a supplement contributing to U_k

for each case. The new medium has resistivity ρ_k. Each image has a position exterior to the region to whose potential it contributes.

Image Sequences

If there are two or more boundaries, and the original pole lies in the interior region G_1, the first transflection may be upward at B_1 or downward at B_2. The upward transflection introduces the complement $(1-Q_1)$ into U_0 and the supplement $(-Q_1)$ into U_1. The original pole, the complement, and the supplement satisfy the boundary conditions at B_1. However, the supplement must be transflected downward at B_2 to satisfy the boundary conditions at that surface. The strength of each transflected image is a definite factor times the strength of the original pole or initiating image. After the first upward transflection, the sequence leads to the same analysis as for the first downward transflection. If the sequence beginning with a downward transflection of the original pole is considered as primary, there is a secondary sequence whose images have strengths $(-Q_1)$ times those of the corresponding primary sequence and positions that are those of the corresponding primary sequence with (b) replaced by $(-b)$. Accordingly, the secondary sequence is obtainable directly from the primary sequence.

An exterior image needs no transflection, but if an image is internal it must be transflected across the other boundary of the corresponding region. Accordingly, successive transflections must be across adjacent boundaries.

The reflection factor for the boundary B_k may be written

$$Q_k = \frac{\rho_k - \rho_{k-1}}{\rho_k + \rho_{k-1}}. \tag{4.1}$$

If the initiating image of U_k has a strength m and a depth ζ, the upward transflection is at B_k and produces a supplement of strength $(-Q_k m)$ at depth $2d_k-\zeta$ and a complement of strength $(1-Q_k)m$ at depth ζ. This transflection may be indicated by $k\uparrow$, the supplement by $k\uparrow k$, and the complement by $k\uparrow(k-1)$. The downward transflection is at B_{k+1} and may be indicated by $k\downarrow$. The supplement is $k\downarrow k$, has the strength $(Q_{k+1}m)$, and depth $2d_{k+1}-\zeta$. The complement is $k\downarrow(k+1)$, has the strength $(1+Q_{k+1})m$, and the depth ζ. These are summarized in Table I.

If G_k is a perfect insulator with respect to G_{k-1}, $Q_k=+1$; if G_k is a perfect conductor with respect to G_{k-1}, $Q_k=-1$; for intermediate conditions, $-1<Q_k<+1$. By reversing equation (4.1), the ratio of the resistivity below B_k to that above is

$$\frac{\rho_k}{\rho_{k-1}} = \frac{1+Q_k}{1-Q_k}. \tag{4.2}$$

If G_k is more conducting than G_{k-1}, Q_k is negative; if G_k is more resistive, Q_k is positive. The case $Q_k=0$ corresponds to $\rho_k=\rho_{k-1}$, or lack of a physical boundary and is excluded, except for limiting processes.

TABLE I

TRANSFLECTION PATTERN

Original image in U_k, of strength m, at depth ζ

Transflection			Supplement				Complement			
Kind	Symbol	At	Symbol	In	Depth	Strength	Symbol	In	Depth	Strength
Downward	$k \downarrow$	B_{k+1}	$k \downarrow k$	U_k	$2d_{k+1}-\zeta$	$Q_{k+1}m$	$k \downarrow (k+1)$	U_{k+1}	ζ	$(1+Q_{k+1})m$
Upward	$k \uparrow$	B_k	$k \uparrow k$	U_k	$2d_k \quad -\zeta$	$-Q_k m$	$k \uparrow (k-1)$	U_{k-1}	ζ	$(1-Q_k)m$

In an image sequence, the initiating image of each transflection must be the produced image of the preceding transflection, and the common element need be written only once. For example, the sequence $3 \uparrow 2 \uparrow 1$ represents the transflection $3 \uparrow 2$ followed by the transflection $2 \uparrow 1$, without confusion.

Exterior Images

An exterior image can come only from an adjoining interior image and is not transflected again. Accordingly, determination of exterior images may be made after all interior images have been determined.

Types

The introduction of a new boundary does not affect the images previously determined to satisfy the potential conditions existing before the introduction. The effect of the new boundary is to add terms to the potentials already determined and such images and the corresponding potential terms may be considered to be of the "type" indicated by the index of the new boundary. The original source is of type zero, and the images due to a single boundary are of type one.

For a space of n boundaries,

$$U_j = \sum_{k=0}^{n-1} U_{jk} + U_{jn} \qquad (0 \leqq j \leqq n), \tag{5}$$

where U_{jk} is independent of n and U_{jv} is the type v potential over the region G_j $(0 \leqq v \leqq n)$. The solution of the problem with n boundaries proceeds from the solution of the problem with $(n-1)$ boundaries. The boundary conditions must be checked at B_k for $U_{k-1,n}$ and U_{kn} $(k<n)$ and at B_n for $U_{n-1,n-1}$, $U_{n-1,n}$, and U_{nn}.

Chains

As successive transflections must be across adjacent boundaries, it is convenient to consider them in pairs or as links of a chain. If there are n boundaries, the first transflection leading to a type n image is due to a downward transflection across B_n of a type $(n-1)$ image in U_{n-1}. Accordingly, first transflection of a type

n link must be across B_n or $B_{n-2\alpha}$, where α is a positive integer less than $(1/2)(n-1)$. The image determined by a chain may be called a "chain image."

If the number of transflections in a type n sequence is odd, the sequence may be considered as the corresponding chain with its last transflection deleted, and the corresponding image may be called an associated image. The associated images may be determined from the chain images.

A link that converts an image into another in the same potential may be called a "shift," otherwise a "transfer." Thus, the link $k \uparrow k \downarrow k$ is a $[kk]$ shift, whereas the link $k \uparrow k-1 \uparrow k-2$ is a $[k, k-2]$ transfer. A transfer may lead to an adjoining region or one separated from the initiating region by a single region. For continuity, the initial element of a link must be the terminal element of the preceding link. As the shifts do not change the region of the link, successive transfers must be connected by a common element.

A chain with a selected sequence of transfers and a selected number of shifts may have the shifts distributed among the corresponding gaps between the transfers. If the numbers of links of each kind are fixed, the end position and strength of the produced image is determined. Accordingly, the image strength of the total image produced by chains of a selected pattern of transfers is the product of the strength of a single chain image of that pattern and the number of ways the shifts can be distributed among the transfers.

Each link produces an image whose strength is a fixed multiple of the originating image, independently of the position of the link in the chain. Accordingly, if the factor f_{jk} indicates the multiple corresponding to the link $[jk]$ and that link occurs (jk) times in a chain, the total multiple due to that type of link is $f_{jk}^{(jk)}$ and the strength of the final image is the product of $f_{jk}^{(jk)}$ taken over all possible links.

Similarly, each link converts a depth ζ into a depth ζ or $2d-\zeta$, where d is the depth of the transflection boundary, below B_1. Accordingly, every image produced by a chain must be in one of four groups $\pm[2ud+b]$, where ud represents the sum of the various boundary depths, each multiplied by a factor determined by the number of times that boundary is used in transflections. This will become clearer in applications to specific problems.

It is convenient for some purposes to use a cycle that produces a chain image in the same potential as the potential of the initiating image and not having that potential by any link within the cycle. Thus, a cycle represents a single "round-trip" from one medium to another and return, considering only complete links.

Summary

In the discussion of the physical problem, it has been shown that the solution of the problem for n boundaries may be reduced to the following steps, taken in order.

1. Solve the problem for $(n-1)$ boundaries.
2. Starting with the exterior images of U_{n-1} of type $(n-1)$, determine the

primary interior chain images of type n, calculating the depth and strength of each.

3. Determine the secondary interior chain images of type n.
4. Determine the associated interior images of type n.
5. Determine the exterior images for U_0 and U_n.
6. Each potential involved is the algebraic sum of terms of the form m/r where m is the strength of a specific image and r is the distance of the test point from that image. The value of r depends on the displacement of the test point from the axis and on the difference in the depths of the image and test point.

For all problems of horizontal layering, a table for r may be prepared with one argument the value of z_ω, the depth of the image, relatively to the depth of the potential test point and the other the displacement of the test point. For a selected observing technique, a distance function may be prepared with the depth of the image as one argument and the parameter of the measuring system as the second. The distance function depends only on the geometry of the problem so that the same table may be used for all problems of this kind after the separate image depths and measuring electrode positions have been determined.

The image strengths depend only on the various resistivities and not on the geometry. Accordingly, a table of image strengths may be prepared for each selected set of resistivities. Each term of the potentials is the product of the strength and the distance function for the corresponding image, and each potential is the algebraic sum of such terms for all images contributing to it.

TWO-BOUNDARY PROBLEM

General Case

For the two-boundary problem, there is only one interior region, G_1, and $n=2$. The original unit pole is located in G_1, at a depth b below the upper boundary, B_1. As there is only one thickness, $h_1=d_2=h$, the subscript is not needed.

The type zero image is the original unit pole, and the only type zero potential is

$$U_{10} = 1/r, \tag{5.1}$$

where

$$r^2 = l^2 + (z - b)^2. \tag{1.2}$$

Type one potentials are introduced by the boundary B_1 and have the values [by equations (3)]

$$U_{01} = (1 - Q_1)/r, \tag{5.21}$$

$$U_{11} = -Q_1/r_2, \tag{5.22}$$

where

$$r_2^2 = l^2 + (z + b)^2, \tag{5.3}$$

$$Q_1 = \frac{\rho_1 - \rho_0}{\rho_1 + \rho_0}. \tag{5.4}$$

The primary type one image of U_1 is the original unit pole at depth $(+b)$. The only chain link has the form $[11] = 1 \downarrow 1 \uparrow 1$ and converts an image of strength m and depth ζ to one of strength $(-Q_1Q_2)m$ and depth $\zeta - 2h$. Accordingly, for a chain of u links, the primary chain image has a strength $(-Q_1)^u Q_2^u$ and depth $-(2uh-b)$. The secondary chain image has the strength $(-Q_1)^{u+1}Q_2^u$ and depth $-(2uh+b)$. If the chain image has the strength m and depth z, whereas the associated image has the strength μ and depth ζ, it follows from the fact that the second transflection of a link is $1 \uparrow 1$ that $\mu = m/(-Q_1)$ and $\zeta = -z$ so that the primary associated image has the strength $(-Q_1)^{u-1}Q_2^u$ and depth $(2uh-b)$, and the secondary associated image has the strength $(-Q_1)^u Q_2^u$ and depth $(2uh+b)$.

An image in U_0 can be produced only as the complement of an upward transflection of an associated image. Hence, corresponding to a chain of u links, the primary U_0 image has a strength $(1-Q_1)(-Q_1)^{u-1}Q_2^u$ and depth $(2uh-b)$, and the secondary U_0 image has a strength $(1-Q_1)(-Q_1)^u Q_2^u$ and a depth $(2uh+b)$.

A primary image of U_2 must be produced by the original pole or a primary chain image by a downward transflection at B_2. Accordingly, the primary U_2 images have the strengths $(1+Q_2)$ at depth b and $(1+Q_2)(-Q_1Q_2)^u$ at depth $-(2uh-b)$, and the secondary U_2 images have the strengths $(1+Q_2)(-Q_1)$ at depth $(-b)$ and $(1+Q_2)(-Q_1)^{u+1}Q_2^u$ at depth $-(2uh+b)$.

The notation

$$z_{u-1,1} = -[2(u-1)h - b], \tag{6.11}$$

$$z_{u-1,2} = -[2(u-1)h + b], \tag{6.12}$$

$$z_{u-1,3} = 2(u-1)h - b, \tag{6.13}$$

$$z_{u-1,4} = 2(u-1)h + b, \tag{6.14}$$

suggests the type two image strengths derived above in the form:

$$m_{0u3} = (1 - Q_1)(-Q_1)^{u-1}Q_2^u, \tag{6.211}$$

$$m_{0u4} = (1 - Q_1)(-Q_1)^u Q_2^u, \tag{6.212}$$

$$m_{1u1} = (-Q_1)^u Q_2^u, \tag{6.221}$$

$$m_{1u2} = (-Q_1)^{u+1}Q_2^u, \tag{6.222}$$

$$m_{1u3} = (-Q_1)^{u-1}Q_2^u, \tag{6.223}$$

$$m_{1u4} = (-Q_1)^u Q_2^u, \tag{6.224}$$

$$m_{2,u-1,1} = (1 + Q_2)(-Q_1)^{u-1} Q_2^{u-1}, \tag{6.231}$$

$$m_{2,u-1,2} = (1 + Q_2)(-Q_1)^u Q_2^{u-1}. \tag{6.232}$$

The type two potentials are:

$$U_{02} = (1 - Q_1) \sum (-Q_1)^{u-1} Q_2^u \left(\frac{1}{r_{u3}} + \frac{-Q_1}{r_{u4}}\right), \tag{6.31}$$

$$U_{12} = \sum (-Q_1)^{u-1} Q_2^u \left(\frac{-Q_1}{r_{u1}} + \frac{Q_1^2}{r_{u2}} + \frac{1}{r_{u3}} + \frac{-Q_1}{r_{u4}}\right), \tag{6.32}$$

$$U_{22} = (1 + Q_2) \sum (-Q_1)^{u-1} Q_2^{u-1} \left(\frac{1}{r_{u-1,1}} + \frac{-Q_1}{r_{u-1,2}}\right), \tag{6.33}$$

where

$$r_{u-1,k}^2 = l^2 + (z - z_{u-1,k})^2, \tag{6.4}$$

and the counter has the range $[1(1)\infty]$.

By equations (1.2), (5.3), and (6.4) it follows that $r_{01} = r_{04} = r$, and $r_{02} = r_{03} = r_2$. By collecting the equations (5) and (6) and replacing r and r_2 by their equivalent values, the total potentials may be written:

$$U_0 = (1 - Q_1) \sum (-Q_1)^{u-1} Q_2^{u-1} \left(\frac{Q_2}{r_{u3}} + \frac{1}{r_{u-1,4}}\right), \tag{6.51}$$

$$U_1 = \sum (-Q_1)^{u-1} Q_2^{u-1} \left(\frac{1}{r_{u-1,2}} + \frac{-Q_1}{r_{u-1,2}} + \frac{Q_2}{r_{u3}} + \frac{(-Q_1)Q_2}{r_{u4}}\right), \tag{6.52}$$

$$U_2 = (1 + Q_2) \sum (-Q_1)^{u-1} Q_2^{u-1} \left(\frac{1}{r_{u-1,1}} + \frac{-Q_1}{r_{u-1,2}}\right). \tag{6.53}$$

These potentials satisfy the boundary conditions and agree with published results, except for notation (Roman, 1931).

GEOPHYSICAL CASE

For the geophysical case, $\rho_0 = \infty$, and $z = b = 0$. Accordingly, $Q_1 = -1$, and $r_{u-1,k}^2 = l^2 + [2(u-1)h]^2$ is independent of k so that the subscript k may be dropped. Hence, as $r_0 = e$, the potential at the earth's surface is

$$U = \frac{2}{l} + 4 \sum \frac{Q^u}{r_u}, \tag{6.6}$$

whether calculated from U_0 or U_1 in equations (6.5).

THREE-BOUNDARY PROBLEM

General Case

For the three-boundary problem, the interior regions are G_1 and G_2, the value of d_1 is zero, and there are two thicknesses $h_1 = d_2$ and $h_2 = d_3 - d_2$. The transflection sequences of type 3 are based on the type 2 images of U_2 in the two-boundary problem, and only type 3 potentials are needed. The first transflection is downward at the boundary B_3 so that the links are of the form odd-even.

As a convenience of notation, the depth groups may be written similarly to those of the two-boundary problem:

$$z_{s-1,v-1,1} = -[2(s-1)h_1 + 2(v-1)h_2 - b], \tag{7.11}$$

$$z_{s-1,v-1,2} = -[2(s-1)h_1 + 2(v-1)h_2 + b], \tag{7.12}$$

$$z_{s-1,v-1,3} = 2(s-1)h_1 + 2(v-1)h_2 - b, \tag{7.13}$$

$$z_{s-1,v-1,4} = 2(s-1)h_1 + 2(v-1)h_2 + b, \tag{7.14}$$

where s and v are positive integers, zero excluded. Also,

$$r^2_{s-1,v-1,k} = l^2 + [z - z_{s-1,v-1,k}]^2. \tag{7.15}$$

The primary starting images are given by

$$m_{2,u-1,1} = (1 + Q_2)(-Q_1)^{u-1}Q_2^{u-1}, \tag{7.21}$$

$$z_{u-1,1} = -[2(u-1)h_1 - b], \tag{7.22}$$

and the secondary starting images by

$$m_{2,u-1,2} = (1 + Q_2)(-Q_1)^{u}Q_2^{u-1}, \tag{7.23}$$

$$z_{u-1,2} = -[2(u-1)h_1 - b]. \tag{7.24}$$

Transflection Links

An interior image can be a 1 or a 2, i.e., it can contribute to U_1 or U_2. Such images can be transflected into interior images in six ways, of which two are odd (at B_1 or B_3) and four are even (at B_2). It follows that there are only four possible links for interior chains:

$$[11] = 1 \uparrow 1 \downarrow 1, \quad [12] = 1 \uparrow 1 \downarrow 2, \quad [21] = 2 \downarrow 2 \uparrow 1,$$

and

$$[22] = 2 \downarrow 2 \uparrow 2.$$

Except for the image $m_{2,0,1}$, each starting image has a negative depth so that the depths of images in 2 may be treated as negative and those in 1 as positive. Appli-

TABLE II

THREE-BOUNDARY TRANSFLECTION LINKS

Link	Strength		Depth	
	Initiating	Produced	Initiating	Produced
11	m	$-Q_1Q_2m$	ζ	$\zeta+2h_1$
12	m	$-Q_1(1+Q_2)m$	ζ	$-\zeta$
21	m	$Q_2(1-Q_2)m$	$-\zeta$	$\zeta+2h_1+2h_2$
22	m	$-Q_2Q_2m$	$-\zeta$	$-(\zeta+2h_2)$

cation of the transflections shown in Table I leads to Table II for three-boundary transflection links.

The first link of a type 3 chain must be a [21] transfer or a [22] shift. The chain consists entirely of shifts or the first transfer is [21]. The chain may be free of cycles or contain cycles [212]. The chains may be analyzed according to the final link and the presence or absence of cycles. For a selected number of cycles and selected final link, the shifts must be distributed between the transfers; and, as the position and strength of the chain image depend on the number of each type of transflection contained, but not on their order, the image for a chain of specified frequencies of links must be weighted according to the number of distinct ways the chain can be arranged. As the transfers must alternate between [21] and [12], the weight is the number of distinct ways in which the shifts can be distributed among the transfers.

Distribution Factor

For $m \geqq 1$ and $n \geqq 2$, the distribution factor $\{m:n\}$ (Roman, 1933, p. 123) may be defined as the number of distinct ways in which m like elements can be distributed in n ordered groups if all elements are used in each distribution; blank groups are permitted, and order within a group is disregarded. If the n groups are formed by $(n-1)$ like separators, the elements and separators can be arranged in $(m+n-1)!$ ways, the elements among themselves in $m!$ ways, and the separators among themselves in $(n-1)!$ ways, so that

$$\{m:n\} = \frac{(m+n-1)!}{m!(n-1)!} \qquad \binom{m \geqq 1}{n \geqq 2}. \tag{7.31}$$

If $m=0$, and $n \geqq 1$, all groups must be blank, and if there is only one group, all elements must fall in that group, so that

$$\{0:n\} = \{m:1\} = 1 \qquad (m \geqq 0,\ n \geqq 1). \tag{7.32}$$

There cannot be a negative number of elements or less than one group so that

$$\{m:n\} = 0 \qquad (m < 0 \text{ or } n < 1). \tag{7.33}$$

Numerous properties of the distribution factor have been published (Roman, 1933), but this paper includes only those specifically needed. The change in representation of the distribution factor has been made for simplification but should cause no confusion.

Primary Chain Image Determinations

Examination of Table II shows that every image falls into one of the groups indicated by equations (7.1). For a selected potential, all images corresponding to the same set of values (s, v, k) may be considered as synthesized into a single image. The values of z may be the same for two images, but the images are treated as distinct unless the indices coincide. A type 3 image is designated as follows. The first index indicates the potential to which the image contributes, the next three indicate the counters of the set and the image group, and additional indices indicate partial sets derived in the development and to be synthesized.

The number of $[jk]$ links in a chain is designated by (jk) where j and k may be identical or distinct. The ratio of the image strength produced by a transflection to that initiating it is designated by f_{jk}.

Unless stated to the contrary, every counter is positive, excluding zero. The upper limits may be determined by equation (7.33) so that sums may have a finite or infinite number of terms, according to conditions. Counters occurring outside of a summation are fixed for that summation, and all others are used in the summation. These conventions permit a single summation sign to be used for multiple summations and remove the need of indicating limits for each sum. As these limits are often dependent on the relative values of the parameters, the convenience is important in avoiding a complicated symbolism or separating possible cases.

By Table II, a transfer changes the sign of the depth and a shift does not. A $[12]$ transfer leaves the magnitude of the depth unchanged, a $[11]$ shift increases it by $2h_1$, a $[22]$ shift increases it by $2h_2$, and a $[21]$ transfer increases it by $2h_1+2h_2$. As the primary starting image has the depth $-[2(u-1)h_1-b]$, the depth of the primary chain image is

$$(-1)^{(21)+(12)+1}\{[(21)+(11)+u-1]2h_1+[(22)+(21)]2h_2-b\}.$$

The primary chain image has the strength

$$(1+Q_2)(-Q_1Q_2)^{u-1}f_{11}^{(11)}f_{12}^{(12)}f_{21}^{(21)}f_{22}^{(22)}$$

which may be written variously. In particular, the strength of the chain image is

$$(1+Q_1)f_{11}^{(11)+u-1}f_{12}^{(12)}f_{21}^{(21)}f_{22}^{(22)}=-Q_1^{-1}f_{11}^{(11)+u-1}f_{12}^{(12)+1}f_{21}^{(21)}f_{22}^{(22)}.$$

Final Link [11], without Cycles

If the final link is a [11] shift and the chain contains no cycles, it must have a single [21] transfer and no [12] transfers. There must be at least one [11] shift, and [22] shifts may be absent or present. Accordingly, $(22)=p-1$, $(21)=1$, $(12)=0$, and $(11)=q$. All [22] shifts must precede the transfer, and all [11] shifts must follow it, so that there is only one chain of this kind. The corresponding image is

$$m_{1;q+u,p,3;1} = -Q_1^{-1} f_{11}^{q+u-1} f_{12} f_{21} f_{22}^{p-1}. \tag{8.11}$$

The notation

$$L_1 = f_{11}^{-1} f_{12} f_{21} f_{22}^{-1} = 1 - Q_2^{-2} = -Q_2^{-2}(1 - Q_2^2) \tag{9.1}$$

permits the writing of equation (8.11) as

$$m_{1;q+u,p,3;1} = -Q_1^{-1} f_{11}^{q+u} f_{22}^{p} L_1. \tag{8.12}$$

The quantity $q+u$ may have any positive value above 1 so that it may be written $q+u=s+1$. Similarly p may be replaced by v. The choice of v determines p, but the choice of s does not determine q or u. For each possible value of q, a value of u is determined by s; and as q can vary from 1 to s, there will be s image chains of this kind. Thus, the weight of this chain image is s and equation (8.12) may be replaced by

$$m_{1;s+1,v,3;1} = -sQ_1^{-1} f_{11}^{s+1} f_{22}^{v} L_1. \tag{8.13}$$

Final Link [11], with Cycles

If the final link is [11] and the chain contains α cycles, there must be α [12] transfers and $(\alpha+1)$ [21] transfers, where α is a positive integer. There must be at least one [11] shift, whereas [22] shifts may be present or absent. Accordingly, $(22)=p-1$, $(21)=\alpha+1$, $(12)=\alpha$, and $(11)=q$. The [22] shifts may occur ahead of each cycle, or after the final cycle, so that they can occur in $\alpha+1$ groups and distributed in $\{p-1:\alpha+1\}$ ways. One [11] shift must be final, but the others can occur within the cycles or after the last [21] transfer so that they can be distributed in $\{q-1:\alpha+1\}$ ways. As these two distributions are independent of each other, the number of distributions taken jointly is their product so that there are $\{q-1:\alpha+1\}\{p-1:\alpha+1\}$ chains for each set of values (α, p, q).

The depth of this chain image is $(q+\alpha+u)2h_1+(p+\alpha)2h_2-b$. The first coefficient must exceed 2 and the second must exceed 1. Hence, they may be written $s+2$ and $v+1$, respectively. Thus, $q=s-\alpha-u+2$ and $p=v-\alpha+1$ determine p and q for each set of values (α, u, s, v). Hence, the image for this chain

specification is

$$m_{1;s+2,v+1,3;2}$$

$$= -Q_1^{-1}\sum f_{11}^{q+u-1}f_{12}^{\alpha+1}f_{21}^{\alpha+1}f_{22}^{p-1}\{q-1:\alpha+1\}\{p-1:\alpha+1\},$$

$$= -Q_1^{-1}\sum f_{11}^{s-\alpha+1}f_{12}^{\alpha+1}f_{21}^{\alpha+1}f_{22}^{v-\alpha}\{s-\alpha-u+1:\alpha+1\}\{v-\alpha:\alpha+1\},$$

$$= -Q_1^{-1}f_{11}^{s+2}f_{22}^{v+1}\sum\{s-\alpha-u+1:\alpha+1\}\{v-\alpha:\alpha+1\}L_1^{\alpha+1}. \qquad (8.21)$$

In this equation, s and v are fixed, whereas α and u are positive counters for which $s-\alpha-u+1\geqq 0$, and $\alpha\leqq v$. For a selected value of α, the summation in u may be performed by the *linear summation formula* [Roman, 1933, equation (6.6)]:

$$\sum\{m-k:u\} = \{m-1:u+1\} \qquad (9.2)$$

leading to the image:

$$m_{1;s+2,v+1,3;2} = -Q_1^{-1}f_{11}^{s+2}f_{22}^{v+1}\sum\{s-\alpha:\alpha+2\}\{v-\alpha:\alpha+1\}L_1^{\alpha+1}. \qquad (8.22)$$

Final Link [11], Total Images

If $s=1$, $v=1$, or both, the primary chain image due to a final link [11] is given by equation (8.13), as equation (8.22) makes no contribution to the resulting image. For both counters s and v above 1, equation (8.13) may be written

$$m_{1;s+2,v+1,3;1} = -(s+1)Q_1^{-1}f_{11}^{s+2}f_{22}^{v+1}L_1. \qquad (8.14)$$

Hence, the total image for such a chain ending in [11] is

$$m_{1;s+2,v+1,3;2}$$

$$= -Q_1^{-1}f_{11}^{s+2}f_{22}^{v+1}L_1[(s+1)+\sum\{s-\alpha:\alpha+2\}\{v-\alpha:\alpha+1\}L_1^{\alpha}]. \qquad (8.31)$$

For $\alpha=0$, the summand reduces to $\{s:2\}\{v:1\}=s+1$ so that the isolated term may be absorbed in the sum and the counter α retarded by unity, leading to:

$$m_{1;s+2,v+1,3;3} = -Q_1^{-1}f_{11}^{s+2}f_{22}^{v+1}\sum\{s-\alpha+1:\alpha+1\}\{v-\alpha+1:\alpha\}L_1^{\alpha}. \qquad (8.32)$$

For $s=0$, or $v=0$, or both, equation (8.32) gives the same value as equation (8.13) for $s=1$, $v=1$, or both, respectively. Hence, the total primary chain image for a final link [11] is

$$m_{1;s+1,v,3;4} = -Q_1^{-1}f_{11}^{s+1}f_{22}^{v}\sum\{s-\alpha:\alpha+1\}\{v-\alpha:\alpha\}L_1^{\alpha}. \qquad (8.33)$$

Final Link [21], *without Cycles*

If the primary chain has a final link [21] and no cycles, it is evident that (22) $=p-1$, (21) $=1$, and (11) $=$ (12) $=0$. All shifts must precede the single transfer, and the image is

$$m_{1;s,v,3;5} = -Q_1^{-1} f_{11}^{s-1} f_{12} f_{21} f_{22}^{v-1} = -Q_1^{-1} f_{11}^{s} f_{22}^{v} L_1. \tag{8.41}$$

Final Link [21], *with Cycles*

If the primary chain has a final link [21] and α cycles, then the [22] shifts can precede, lie between, or follow the cycles, and the [11] shifts must lie within the cycles. Accordingly, (22) $=p-1$, (21) $=\alpha+1$, (12) $=\alpha$, (11) $=q-1$, and the weight is

$$\{p-1:\alpha+1\}\{q-1:\alpha\}.$$

Hence the image is

$$\begin{aligned} m_{1;s+1,v+1,3;6} &= -Q_1^{-1} \sum f_{11}^{s-\alpha} f_{12}^{\alpha+1} f_{21}^{\alpha+1} f_{22}^{v-\alpha} \{s-\alpha-u+1:\alpha\}\{v-\alpha:\alpha+1\}, \\ &= -Q_1^{-1} f_{11}^{s+1} f_{22}^{v+1} \sum \{s-\alpha-u+1:\alpha\}\{v-\alpha:\alpha+1\} L_1^{\alpha+1}, \\ &= -Q_1^{-1} f_{11}^{s+1} f_{22}^{v+1} \sum \{s-\alpha:\alpha+1\}\{v-\alpha:\alpha+1\} L_1^{\alpha+1}. \end{aligned} \tag{8.42}$$

Final Link [21], *Total Images*

As for chains ending in [21], only the image given by equation (8.41) contributes to $m_{1;s,v,3}$, if either s or v is one; whereas both of the images given by equations (8.41) and (8.42) contribute if s and v each exceed one. As for the final link [11], the two equations condense to

$$m_{1;s,v,3;7} = -Q_1^{-1} f_{11}^{s} f_{22}^{v} \sum \{s-\alpha:\alpha\}\{v-\alpha:\alpha\} L_1^{\alpha}, \tag{8.43}$$

which gives the primary image for a chain ending in [21].

Primary Chain Images of U_1

An image chain of U_1 must end in [11] or [21]. If the second index is one, only the image of equation (8.43) can contribute, but, for larger values, the images of equation (8.33) and of equation (8.43) can contribute. As in the condensations for chains ending in [11] or [21], the primary chain images of U_1 condense to

$$m_{1;s,v,3} = -Q_1^{-1} f_{11}^{s} f_{22}^{v} \sum \{s-\alpha:\alpha+1\}\{v-\alpha:\alpha\} L_1^{\alpha}, \tag{8.5}$$

upon utilizing the *reduction formula* [Roman, 1933, equation (6.4)]

$$\{m:n\} = \{m:n-1\} + \{m-1:n\}, \tag{9.2}$$

which holds unless $m=n-1=0$, a case that is not needed in the present paper.

Final Link [12]

If the final link is [12], the chain must contain at least one cycle, a cycle being terminal. The number of shifts is arbitrary. Accordingly, $(22)=p-1$, $(21)=(12)=\alpha$, $(11)=q-1$. The [22] shifts must precede the cycles, and the [11] shifts must lie within the cycles so that the weight is $\{p-1:\alpha\}\{q-1:\alpha\}$. The primary image for the chain ending in [12] is

$$m_{2;s,v,1;1} = -Q_1^{-1} f_{11}^{s} f_{12} f_{22}^{v} \sum \{s-\alpha:\alpha+1\}\{v-\alpha:\alpha\} L_1^{\alpha}. \tag{10.1}$$

Final Link [22], *without Cycles*

A chain that ends in [22] and has no cycles must consist entirely of shifts, so that $(22)=p$ and $(21)=(12)=(11)=0$. Accordingly, the corresponding image is

$$m_{2;s-1,v,1;2} = -Q_1^{-1} f_{11}^{s-1} f_{12} f_{22}^{v}. \tag{10.21}$$

Final Link [22], *with Cycles*

For a chain ending in [22] and containing α cycles, the [22] shifts can occur before, between, or after the cycles, and the [11] shifts must occur within the cycles. Accordingly, $(22)=p$, $(21)=(12)=\alpha$, $(11)=q-1$, and the weight is $\{p-1:\alpha+1\}\{q-1:\alpha\}$. The corresponding primary chain image is

$$m_{2;s,v+1,1;3} = -Q_1^{-1} f_{11}^{s} f_{12} f_{22}^{v+1} \sum \{s-\alpha:\alpha+1\}\{v-\alpha:\alpha+1\} L_1^{\alpha}. \tag{10.22}$$

Final Link [22], *Total Images*

The images of equations (10.2) condense to

$$m_{2;s-1,v,1;4} = -Q_1^{-1} f_{11}^{s-1} f_{12} f_{22}^{v} \sum \{s-\alpha:\alpha\}\{v-\alpha:\alpha\} L_1^{\alpha-1}. \tag{10.23}$$

Primary Chain Images of U_2

For the total primary images for chains of U_2 equations (10.1) and (10.23) condense to

$$m_{2;s-1,v,1} = -Q_1^{-1} f_{11}^{s-1} f_{12} f_{22}^{v} \sum \{s-\alpha:\alpha\}\{v-\alpha+1:\alpha\} L_1^{\alpha-1}. \tag{10.3}$$

Associated Images

The image associated with a chain image is caused by deleting the last transflection of the chain sequence. The image due to a chain ending in [21] is the

complement of the transflection of its associated image in an upward transflection at B_2. The image due to a chain ending in [22] is the supplement of the transflection of its associated image in the same transflection. Hence these two associated images are actually one, and this is given by

$$m_{2;s,v,3} = Q_3(1 + Q_2)f_{11}^{s-1}f_{22}^{v-1}\sum \{s - \alpha:\alpha\}\{v - \alpha:\alpha\}L_1^{a-1}. \qquad (11.1)$$

Similarly, an associated image transflects as a complement into the image of a chain ending in [12] and as the supplement into the image of a chain ending in [11], both by a downward transflection at B_2. The corresponding associated image is

$$m_{1;s,v,1} = f_{11}^{s}f_{22}^{v}\sum \{s - \alpha:\alpha + 1\}\{v - \alpha:\alpha\}L_1^{a}. \qquad (11.2)$$

Exterior Images

The exterior images are in U_0 and U_3. The former occur as the complement of an upward transflection at B_1 of an image due to a chain image in U_1. Accordingly, they are given for the primary set, by

$$m_{0;s,v,3} = Q_2(1 - Q_1)f_{11}^{s-1}f_{22}^{v}\sum \{s - \alpha:\alpha + 1\}\{v - \alpha:\alpha\}L_1^{a}. \qquad (12.1)$$

The latter occur as the complement of a downward transflection at B_3 of a type 2 image or a chain image of U_2. Accordingly, they are given, for the primary set, by

$$m_{3;s-1,v-1,1} = (1 + Q_2)(1 + Q_3)f_{11}^{s-1}f_{22}^{v-1}\sum \{s - \alpha:\alpha\}\{v - \alpha:\alpha)L_1^{a-1}. \qquad (12.2)$$

Secondary Images

Each primary image leads to a secondary image whose strength is $(-Q_1)$ as large and whose depth is that of the primary image with the sign of b, the depth of the original current source, reversed.

Potential Expressions

The potential values are expressed by equations (2.13), where the summation extends over all possible values of the counters $\omega = (s, v)$. For each set ω, there may be an image in each of either two or four groups of depths. As emphasis is on type 3 images, the applicable primary images are indicated by equations (12.1); (11.2), (8.5); (10.3), (11.1); and (12.2). These equations involve summations in α, and the corresponding sums may be computed for the parameters s, v, and Q_2, independently of their use in the image strengths, especially for purposes of numerical evaluation.

Image Polynomials

Introduction of the image polynomials:

$$\theta_{sv1} = \sum (-1)^{\alpha-1}\{s-\alpha:\alpha+1\}\{v-\alpha:\alpha\}Q_2^{s+v-2\alpha}(1-Q_2^2)^{\alpha}, \quad (13.11)$$

$$\theta_{sv2} = \sum (-1)^{\alpha-1}\{s-\alpha:\alpha\}\{v-\alpha:\alpha\}Q_2^{s+v-2\alpha}(1-Q_2^2)^{\alpha-1}, \quad (13.12)$$

reduces the primary image strengths to

$$m_{0;s,v,3} = (-1)^{s+v}Q_1^{s-1}(1-Q_1)Q_3^v\theta_{sv1}, \quad (13.21)$$

$$m_{1;s,v,1} = (-1)^{s+v-1}Q_1^sQ_3^v\theta_{sv1}, \quad (13.22)$$

$$m_{1;s,v,3} = (-1)^{s+v}Q_1^{s-1}Q_3^v\theta_{sv1}, \quad (13.23)$$

$$m_{2;s-1,v,1} = (-1)^{s+v-1}Q_1^{s-1}(1+Q_2)Q_3^v\theta_{s,v+1,2}, \quad (13.24)$$

$$m_{2;s,v,3} = (-1)^{s+v}Q_1^{s-1}(1+Q_2)Q_3^v\theta_{sv2}, \quad (13.25)$$

$$m_{3;s-1,v-1,1} = (-1)^{s+v}Q_1^{s-1}(1+Q_2)Q_3^{v-1}(1+Q_3)\theta_{sv2}. \quad (13.26)$$

The image polynomials are polynomials in Q_2 for each pair (s, v), but do not necessarily start with a zero-order term. However, they can be written for each pair (s, v) and then evaluated for each Q_2. The other parts of the image strengths are factors of a single reflection factor so that, for numerical evaluations, the factors involving each reflection factor can be determined and tabulated separately.

The image polynomials possess a symmetry that is convenient in numerical evaluations. By equation (7.31), that defines the distribution factors,

$$\frac{\{s-\alpha:\alpha+1\}\{v-\alpha:\alpha\}}{\{s-\alpha:\alpha\}\{v-\alpha:\alpha+1\}} = \frac{s}{v}, \quad (14.1)$$

which is independent of α, and hence

$$v\theta_{sv1} = s\theta_{vs1}. \quad (14.2)$$

It is evident by inspection of the definition, equation (13.12), that

$$\theta_{sv2} = \theta_{vs2}. \quad (14.3)$$

Accordingly, θ_{sv1} and θ_{sv2} need to be calculated directly only for $s \leqq v$.

Recursion Formulas

Although the images can be determined directly as discussed, a recursion formula is useful as a check on the direct computations or as a shorter method, especially if an electronic computer is at hand.

Equations (13.1) can be condensed to

$$\theta_{svk} = (1 - Q_2^2)^{\beta} \sum (-1)^{\alpha-1} \{s - \alpha : \alpha + \beta\} \{v - \alpha : \alpha\} Q_2^{s+v-2\alpha} (1 - Q_2^2)^{\alpha-1}, \quad (15.1)$$

where $\beta = 1$ for $k = 1$, and $\beta = 0$ for $k = 2$.

For selected values of (s, v, k), equation (15.1) shows that

$$\theta_{s+1,v+1,k} - Q_2\theta_{s+1,v,k} - Q_2\theta_{s,v+1,k} + Q^2\theta_{svk}$$

can be written as

$$(1 - Q_2^2)^{\beta} \sum (-1)^{\alpha-1} Q_2^{s+v-2\alpha+2} (1 - Q_2^2)^{\alpha-1} P,$$

where P for each value of α is the sum of four terms, each the product of a distribution factor involving s and one involving v. The factor P can be expressed as the product of the difference of two distribution factors involving s and the difference of two involving v. By the reduction formula, equation (9.2), each of these differences can be expressed as a single distribution factor. Specifically, the sum of the four original terms reduces to

$$(1 - Q_2^2)^{\beta} \sum (-1)^{\alpha-1} Q_2^{s+v-2\alpha+2} (1 - Q_2^2)^{\alpha-1} \{s - \alpha + 1 : \alpha + \beta - 1\} \{v - \alpha + 1 : \alpha - 1\}.$$

For $\alpha = 1$, the last factor, and hence the term, vanishes. For $\alpha > 1$, the counter α can be advanced by one, and, by comparison with equation (15.1), the value of the entire sum is $-(1 - Q_2^2)\theta_{svk}$. Accordingly, the equality of the original expression and this final one leads to the recursion formula

$$\theta_{s+1,v+1,k} = Q_2\theta_{s+1,v,k} + Q_2\theta_{s,v+1,k} - \theta_{svk}, \quad (15.2)$$

which proceeds from

$$\theta_{111} = 1 - Q_2^2, \quad (15.31)$$

$$\theta_{s+1,1,1} = (s + 1)Q_2^s(1 - Q_2^2), \quad (15.32)$$

$$\theta_{1,v+1,1} = Q_2^v(1 - Q_2^2), \quad (15.33)$$

$$\theta_{112} = 1, \quad (15.34)$$

$$\theta_{s+1,1,2} = Q_2^s, \quad (15.35)$$

$$\theta_{1,v+1,2} = Q_2^v. \quad (15.36)$$

Each image strength is of the form $K(-Q_1)^s(-Q_3)^v\theta_{svk}$, where K is independent of s and v. Accordingly, if $m_{i;s,v,j}$ is written m_{sv} for a selected pair (i, j), the

image strengths satisfy the recursion formula

$$m_{s+1,v+1} = (-Q_2Q_3)m_{s+1,v} - (Q_1Q_2)m_{s,v+1} - (Q_1Q_3)m_{sv}. \tag{15.4}$$

GEOPHYSICAL CASE

For the geophysical case, the current source and potential test points are on the surface of the earth so that $z=b=0$. The upper medium is air, for which $\rho_0=\infty$, so that $Q_1=-1$. The only potential functions of interest are U_0 and U_1 which have the same value at every point of the earth's surface.

The image depths may be written:

$$\begin{aligned} z_{s-1,v-1} &= -z_{s-1,v-1,1} = -z_{s-1,v-1,2} = z_{s-1,v-1,3} = z_{s-1,v-1,4}, \\ &= 2(s-1)h_1 + 2(v-1)h_2. \end{aligned} \tag{16.1}$$

The corresponding distances are

$$r_{s-1,v-1} = r_{s-1,v-1,1} = r_{s-1,v-1,2} = r_{s-1,v-1,3} = r_{s-1,v-1,4}, \tag{16.21}$$

where

$$r^2_{s-1,v-1} = l^2 + z^2_{s-1,v-1}. \tag{16.22}$$

The secondary images coincide with the primary images and have the same strengths. By equations (13.2),

$$m_{0;s,v,3} = m_{0;s,v,4} = -2(-Q_3)^v\theta_{sv1} \tag{16.31}$$

$$m_{1;s,v,1} = m_{1;s,v,2} = m_{1;s,v,3} = m_{1\cdot s,v,4} = -(-Q_3)^v\theta_{sv1}. \tag{16.32}$$

Accordingly, the type 3 surface potential is

$$U_{03} = U_{13} = 4\sum m_{sv}/r_{sv}, \tag{16.41}$$

$$m_{sv} = -(-Q_3)^v\theta_{sv1}. \tag{16.42}$$

As every term of θ_{sv1}, equation (13.11), contains the factor $(1-Q_2^2)$, $\theta_{sv1}=0$ if $Q_2=+1$, for which case $U_{03}=0$. Accordingly, if the second layer is either a perfect conductor or a perfect insulator, with respect to the upper layer, the third layer makes no contribution to the surface potential.

By the recursion formula of equation (15.4),

$$m_{s+1,v+1} = Q_2m_{s,v+1} + Q_3m_{sv} - Q_2Q_3m_{s+1,v}, \tag{16.51}$$

where

$$m_1 = (1-Q_2^2)Q_3, \tag{16.521}$$

$$m_{s+1,1} = (s+1)(1-Q_2^2)Q_2^sQ_3, \tag{16.522}$$

$$m_{1,v+1} = -(1-Q_2^2)Q_2^v(-Q_3)^{v+1}. \tag{16.523}$$

In direct calculation of the image strengths, use should be made of the symmetry of θ_{svl} as given by equation (14.2). For this purpose, direct calculation is needed only for the case $s \leqq v$. Also, if $s+v$ is odd, the factor Q_2 may be removed from the summation to make the power of Q_2 even within the summation. For $s+u$ even, θ_{svl} is a polynomial of degree $(1/2)(s+v)$ in $\xi=Q_2^2$ and $\eta=(1-Q_2^2)$. For $s+v$ odd, θ_{svl}/Q_2 is polynomial of degree $(1/2)(s+v-1)$ in ξ and η. These polynomials have the same value for Q_2 positive or negative and depend on the numerical value of Q_2.

SUMMARY

This paper develops a systematic analysis of the application of Kelvin's method of images to plane parallel boundaries and applies the method to the cases of two and of three boundaries. The results are reduced to the geophysical case in which the upper layer is air and all electrical contacts are on the upper boundary.

Although results have been arranged with numerical computation in mind, no such evaluations are included. For the three-boundary problem, a recursion formula is derived to check the direct calculation of the series.

The potential function is replaced by a set of expressions each of which determines the value of the potential at the points of one region of space. Each of these expressions is the sum of the basic potential m/r, where m is the strength and r the distance from the test point for a specific image, and such terms are added algebraically for all possible images contributing to that potential.

For the problem of n boundaries, the solution consists of two parts, the first being the solution of the problem of $(n-1)$ boundaries obtained by removing the lowest boundary and the second being the contribution of the lowest boundary to each potential expression. The introduction of a new boundary does not change the images previously determined but adds a new set to each, as well as a new potential expression for the lowest layer.

At each boundary, a transflection across that boundary introduces a complementary image, at the position of the initiating image but contributing to the space opposite the one containing the initiating image; and a supplement contributing to the space containing the initiating image but located at the optical image position of the initiating image in the boundary. This leads to a tracing of images by a series of transflections. Successive transflections are at adjacent boundaries leading to a chain of links, each consisting of two transflections. Interior images, between boundary planes, may be chain images, due to a sequence of links, or associated images, obtained by omitting the final transflection from a chain. The primary sequence of images is due to a sequence that started with a downward transflection of the original source. Corresponding to each primary image there is a secondary image due to the supplement of the upward transflection of the original source. Exterior images are obtained as the complements of a transflection at the top or bottom boundary and are not transflected further.

The images fall into four groups in each of which only the coefficients of the thicknesses change in the expression for the image depth. For a single transflection sequence, the image strengths are products of the various transflection factors. But the depth is the same for all chains having the specified frequencies for the different links, independently of their positions in the chains. Hence the chains must be multiplied by their weights to determine the total image.

For the three-boundary problem, the image strengths are expressible as the products of polynomials in the three reflection factors. One of these three factors is an image polynomial that depends only on the reflection factor at the middle boundary and contains a summation over a parameter corresponding to the number of cycles. If the values of this image polynomial are tabulated, images for a specific problem are obtainable by multiplication alone.

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GEOPHYSICS, VOL. XXIV, NO. 3 (JULY, 1959), PP. 510-530, 14 FIGS.

ELECTRICAL PROPERTIES OF SYNTHETIC METALLIFEROUS ORE*

ROBERT B. McEUEN†, JOSEPH W. BERG, JR.†, AND KENNETH L. COOK†

ABSTRACT

Ninety small cores of synthetic metalliferous ore were constructed from solid glass spheres averaging 0.5 mm in diameter, lead spheres 1.0 mm in diameter, and refractory cement. The lead content of the cores varied from zero to 50 percent by frame volume. The effective porosity was controlled by the manufacturing pressure and ranged from 10 to 20 percent. The cores were saturated with NaCl solution. The apparent impedance of the cores was measured with a modified Wheatstone bridge as a function of frequency and current density. The low-frequency effects of induced polarization were separated from the over-all decrease of impedance with increase of frequency by taking advantage of the dependence of these effects upon current density. The over-all decrease of the impedance with frequency and the polarization effects were found dependent upon the effective porosity and the lead content. Both the polarization effects and the over-all decrease of the impedance with frequency increased with decreasing porosity. The induced polarization effects at 10 cps attained a maximum at approximately 15 percent lead content. The impedance of a synthetic ore with a small lead content was found to be *larger* than that of corresponding cores barren of lead.

INTRODUCTION

The electrical properties of rocks are complex. This complexity is increased when conductive particles, such as disseminated sulphides or native metals, occur in the otherwise non-conductive rock frame. An understanding of the electrical properties is necessary in order to evaluate correctly laboratory and field electrical data. Various investigations have been made using both transient- and alternating-current techniques. Transient-current studies have been made by Brant and Gilbert (1952), Bleil (1953), Johnson (1954), Henkel and Van Nostrand (1957), and others. Alternating-current studies have been made by Blau (1933), Hawley (1938), Wait and others (1956), Hallof and others (1957), Mandel and others (1957), and by others.

During the past three years, studies of the electrical properties of synthetic rocks have been made in the Department of Geophysics at the University of Utah principally using alternating-current techniques. The advantage of using synthetic rocks instead of natural rocks is that the physical and chemical properties of the synthetic rocks can be more closely controlled. The general underlying objectives of this research are:

(1) To establish a model for the electrical behavior of rocks, which accounts for the electronic and ionic conduction as well as the physical-chemical phenomenon of "induced polarization"; and

(2) To use this model as an aid in the applied methods of electrical prospecting.

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The object of the research discussed in this paper was to study the fundamental electrical properties of a synthetic ore composed of lead spheres disseminated through an otherwise non-conductive frame. These properties include changes in the apparent impedance resulting from changes in the magnitude and frequency of the applied current and the relationship of these apparent impedance changes to the physical properties of the synthetic ore, such as frame composition and porosity.

EXPERIMENTAL METHODS

Manufacture of the Synthetic Ore

Ninety cylindrically shaped cores, approximately one inch long and $\frac{3}{4}$ inch in diameter, were manufactured by the method developed by Mandel and others (1957). These cores were constructed from solid glass spheres averaging 0.5 mm in diameter, spherical lead shot (American dust) averaging 1.0 mm in diameter, and Grefco refractory cement (General Refractories Company, Philadelphia, Pennsylvania). The percentages, by frame volume, of lead in the cores were 0, 3, 6, 9, 12, 15, 20, 30, and 50. Ten cores were made for each percentage of lead. For all cores, the cement content was 25 percent of the frame volume. The effective porosity of the cores was controlled by the manufacturing pressure (approximately 1,000 to 15,000 psi), and ranged from 10 to 20 percent. All porosities were determined by vacuum techniques and will be referred to as effective porosity throughout this paper.

Apparatus and Experimental Techniques

Apparent impedances were measured using a Wheatstone bridge with a Wagner grounding system (see Figure 1), which eliminated stray capacitance to ground. A 60-cycle reject filter was used to improve the wave form of high frequency signals as seen by the null detector. The null detector was a battery-operated vacuum tube voltmeter. The cell containing the core of synthetic ore was placed in one arm of the bridge. A small variable capacitance, C_1, was used to compensate the intrinsic capacitance of the cell. The bridge system had a flat frequency response, to within one percent, between 10 cps and 20,000 cps. Although the absolute values of the apparent impedances were determined to within only three percent accuracy, the relative values are believed to be within one percent accuracy after correction for non-linearity of the bridge.

The lower part of Figure 1 shows an enlarged diagram of the measurement cell. The cell consisted of a rigid plastic tube and a rubber hose, the inside diameter of which was identical with the outside diameter of the synthetic ore. The hose containing the saturated synthetic ore was inserted through a window into the plastic tube. Both ends of the cell were then filled with an aqueous solution of sodium chloride that was identical with that saturating the synthetic ore. The entire measurement cell was then inserted inside a flexible thin-walled hose, not shown in the figure. To minimize surface conduction along the cylindri-

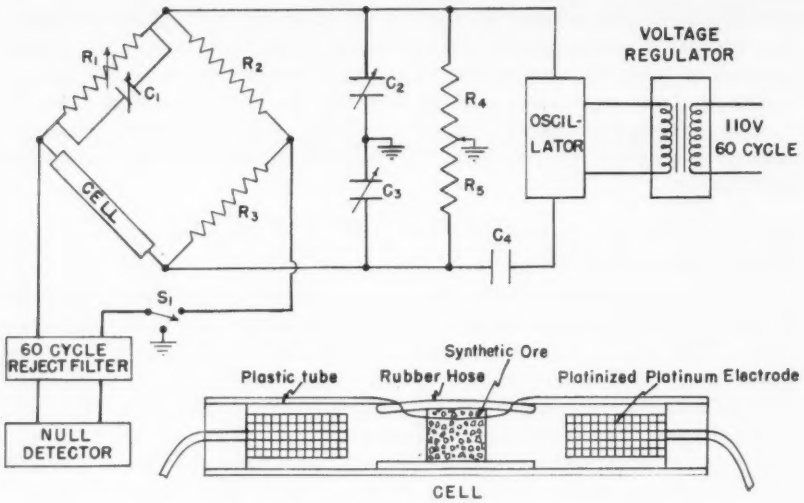

FIG. 1. Bridge circuit and measurement cell.

cal surface of the core, an external clamp was used to apply pressure on the inner hose containing the core. By placing the hose containing the measurement cell in a constant temperature bath, (± 0.1°C.), the drift produced by I^2R heating of the cell during the measurements was minimized. Care was taken to allow the system to attain thermal equilibrium prior to the measurements. Platinized platinum electrodes were used because they were found to be essentially free of polarization effects for the frequencies and current densities used. Silver-silver chloride electrodes were tried but their performance was deemed unsatisfactory as compared with platinized platinum.

For the above cell, the normalized apparent impedance Z_a of the core in ohm-centimeters is given approximately by the following equation, which is derived in the appendix:

$$\mathrm{Z}_a = (Z_{ci} - Z_{co}) \frac{A_c}{l_c} + \rho_e \tag{1}$$

where $(Z_{ci} - Z_{co})$ is the difference between the apparent impedance Z_{ci} (as read in ohms on the impedance bridge) of the system when the core is in the tube, and the apparent impedance Z_{co} (as read in ohms on the impedance bridge) of the system when the core is out of the tube. A_c/l_c is the geometric normalizing constant for the core in centimeters, where A_c is the cross sectional area of the core along a plane perpendicular to the axis of the cylindrical core and l_c is the

length of the core. ρ_e is the resistivity of the electrolyte saturating the core which in this study was 340 ± 10 ohm-centimeters.[1] It will be noted that Z_a is in the units of ohm-centimeters and will be designated in this paper as normalized apparent impedance. It is suggested that the term "impedivity" be used to designate normalized impedance.

The method of investigating the apparent impedance in these experiments was to hold the potential difference across the cell constant for a given specimen as the frequency was varied between 10 and 70,000 cps. This method resulted in a nearly constant current density, within 8 percent, as checked by experimental measurements, over the frequency range in which the impedance was current-density dependent. All potential differences and current densities referred to in this paper are root-mean-square values.

EXPERIMENTAL RESULTS

Figure 2 shows ranges of the variables for three ore samples used in this study. In this figure, normalized apparent impedance is plotted linearly in thousands of ohm-centimeters against the logarithmically plotted frequency in cycles per second. The data are for three cores whose porosity was approximately 13.9 percent in each case and whose percentages of lead by frame volume were 0, 12, and 20. Three different current densities were used for the impedance measurements on each core. The values were J_1, $J_1/2$, and $J_1/10$, where $J_1 = 3.51 \times 10^{-4}$ amp/cm^2. It will be observed that for the core free of lead (see middle curve, Figure 2) there is essentially no variation in the normalized apparent impedance with respect to either frequency or current density. There is considerable variation, however, of the normalized apparent impedance, with both frequency and current density, for the cores containing lead. For these cores, the normalized apparent impedance decreases markedly with increase in frequency. Also, the normalized apparent impedance of these cores is independent of current density only at frequencies above approximately 5,000 cps. It should be emphasized that the dependence of this impedance upon current density at the lower frequencies differentiates it from the usual concept of impedance, and for this reason it is called *apparent* impedance.

The electrical properties of the synthetic ore are complex, and it is desirable to consider the experimental results in the following order:

a) high frequency effects,
b) low frequency effects,
c) correlation between high and low frequency effects, and
d) synthesis of polarization effects.

[1] The sodium chloride solution became somewhat contaminated after saturation of the cores, as evidenced by its decrease in resistivity, probably by salts from impurities in the cement and lead ions from the dissociation of the lead.

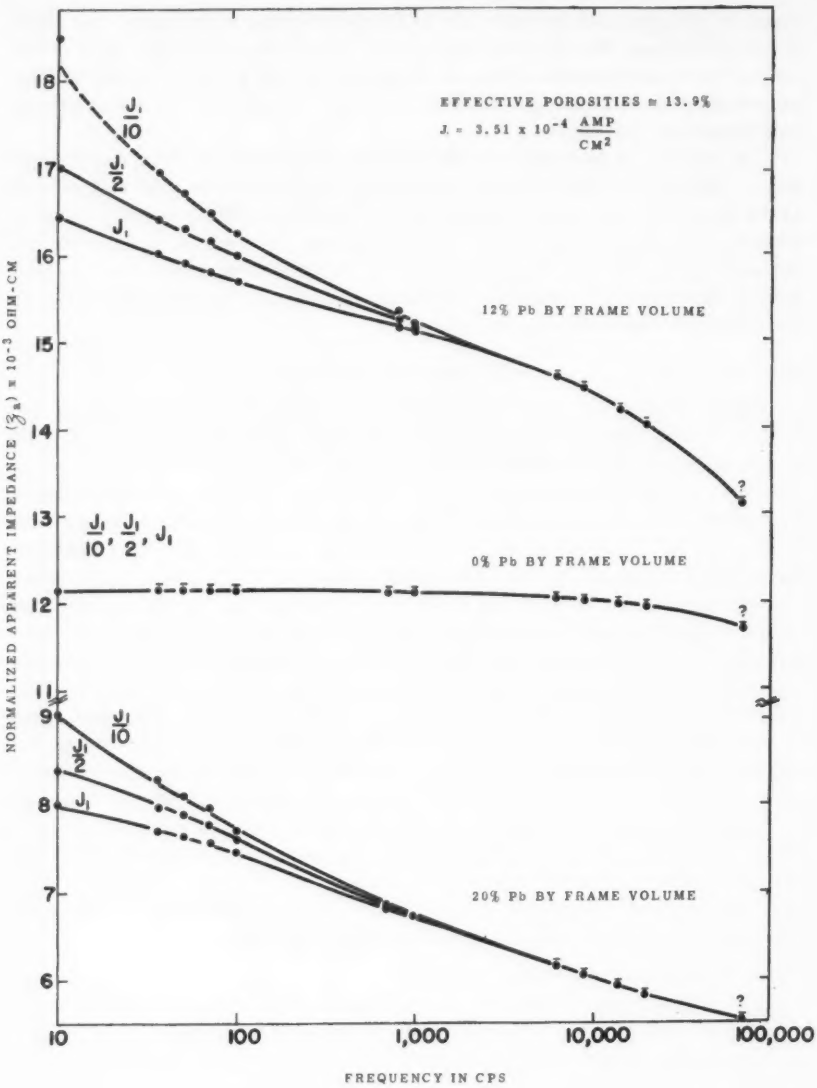

FIG. 2. Normalized apparent impedance versus frequency for three cores containing 0, 12, and 20 percent lead by frame volume. Three different current densities were used.

High Frequency Effects

Figures 3 and 4 show values of the normalized apparent impedance calculated from measurements taken at a constant frequency of 6,365 cps. This particular frequency was chosen for convenience, and it is evident from Figure 2 that it is well above the frequency range where the impedance is dependent upon current

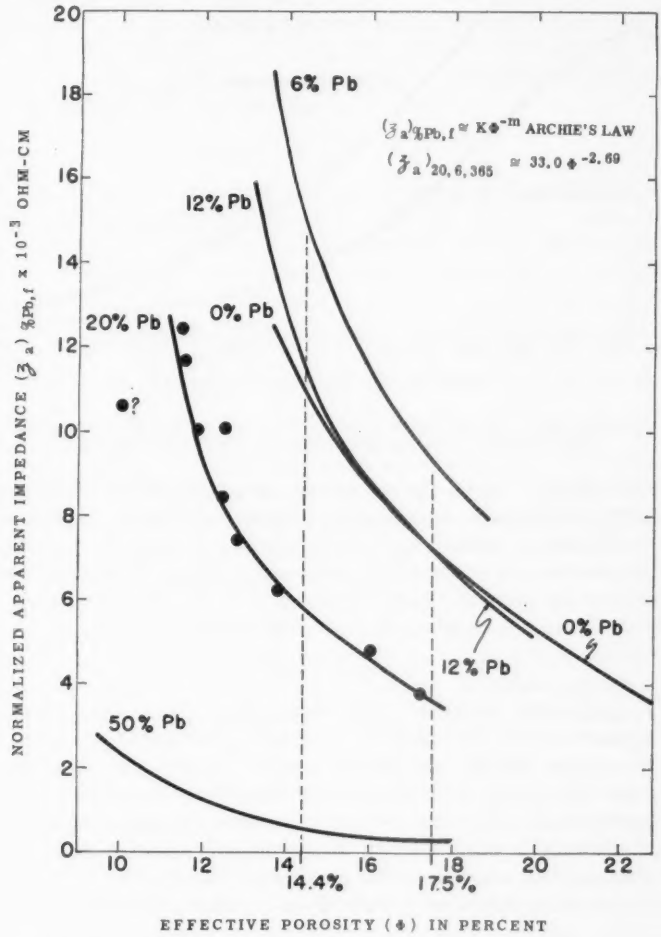

FIG. 3. Normalized apparent impedance at 6,365 cps, versus effective porosity for cores containing 0, 6, 12, 20, and 50 percent lead by frame volume.

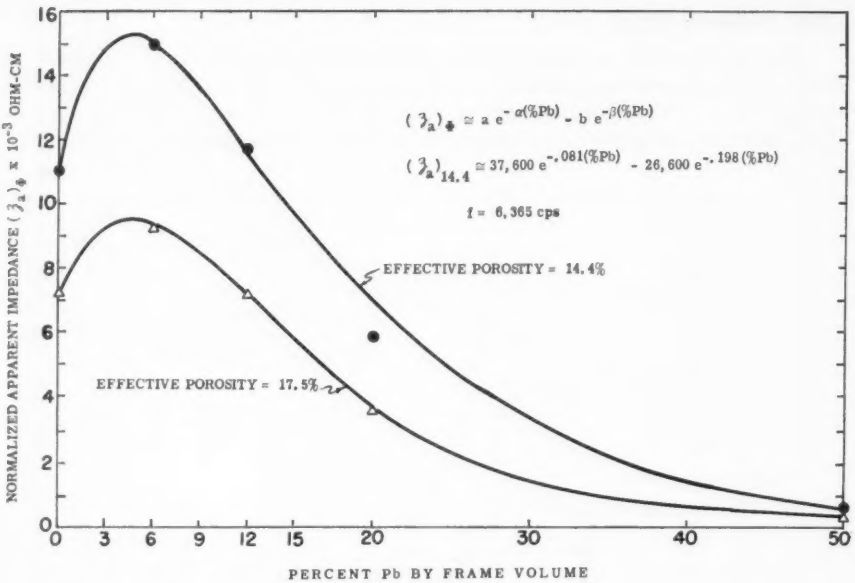
NORMALIZED APPARENT IMPEDANCE $(\mathcal{Z}_a)_\Phi \times 10^{-3}$ OHM-CM
$(\mathcal{Z}_a)_\Phi \cong a\, e^{-\alpha(\%Pb)} - b\, e^{-\beta(\%Pb)}$
$(\mathcal{Z}_a)_{14.4} \cong 37,600\, e^{-.081(\%Pb)} - 26,600\, e^{-.198(\%Pb)}$
$f = 6,365$ cps
EFFECTIVE POROSITY = 14.4%
EFFECTIVE POROSITY = 17.5%
PERCENT Pb BY FRAME VOLUME

FIG. 4. Normalized apparent impedance at 6,365 cps versus percent lead by frame volume for ore with constant effective porosities of 14.4 percent and 17.5 percent.

density. For Figures 3 and 4 the percentages of lead by frame volume are 0, 6, 12, 20, and 50. In Figure 3, the normalized apparent impedance, $\mathcal{Z}_a$, in thousands of ohm-centimeters, is plotted against the effective porosity, Φ, in percent.[2] A curve is shown for each of the above percentages of lead. Points are shown for the ore with 20 percent lead by frame volume to show representative scatter of the data. The data can be approximated by the formula

$$(\mathcal{Z}_a)_{\%\mathrm{Pb},f} = K\Phi^{-m} \qquad (2)$$

where $(\mathcal{Z}_a)_{\%\mathrm{Pb},f}$ is the normalized apparent impedance for a given percentage of lead by frame volume, %Pb, taken at a frequency, f; K and m are constants for a given frame type; and Φ is the effective porosity expressed as a fraction of the total volume of the ore. Thus, the data indicate that at a constant frequency above approximately 5,000 cps and for a constant amount of lead by frame volume, a relationship exists between the normalized apparent impedance and the effective porosity which is similar in form to Archie's law. It will be noted that as the amount of lead by frame volume is decreased from 50 percent to

[2] The point in Figures 3, 6, and 8, for an effective porosity indicated as 10 percent is in error as can be inferred from its location in Figure 9, which indicates that the correct effective porosity is between 11 and 12 percent.

about 6 percent, the normalized apparent impedance increases systematically (see also Figure 4). As the amount of lead by frame volume is decreased further, from 6 percent to zero percent, however, the normalized apparent impedance *decreases* until at zero percent lead by frame volume the curve is nearly superimposed upon the curve for 12 percent lead by frame volume. A possible explanation of this anomalous feature will be given later.

Figure 4 shows the curves obtained from the data of Figure 3 at the two values of constant effective porosity (14.4 percent and 17.5 percent) represented by the dotted lines. The normalized apparent impedance in thousands of ohm-centimeters is plotted against the percentage of lead by frame volume. The data shown can be approximated by the formula

$$(Z_a)_{\Phi,f} = ae^{-\alpha(\%\mathrm{Pb})} - be^{-\beta(\%\mathrm{Pb})} \tag{3}$$

where $(Z_a)_{\Phi,f}$ is the normalized apparent impedance at a constant effective porosity Φ and at a constant frequency f; (%Pb) is the percentage of lead by frame volume; a, b, α, and β are values dependent upon the porosity, frequency, and other factors, when the resistivity of the saturating electrolyte is held constant. Anomalous values of normalized apparent impedance occur such as to give a maximum in the region of 4 percent lead by frame volume. The general shape of these curves has been verified by additional experimentation. The second term on the right-hand side of equation (3) is included to describe this anomalous feature.

It is suggested that a possible explanation of this anomalous effect may be that the electric field is distorted sufficiently when small amounts of lead are introduced into the ore to give a net increase in the length of the conduction paths through the ore. This effect is greater for a porosity of 14.4 percent than for 17.7 percent. The extent to which these anomalous values are dependent upon geometrical and other factors has not been established. Previous work by Mandel and others (1957, Figure 2a), using a frequency of 1,000 cps, showed similar anomalous maxima at about 8 percent lead by frame volume. It has not been determined to what extent small variations in porosity may have influenced their results, such as their observed decrease in the normalized apparent impedance for small increases in the lead content in the range from zero to approximately 6 percent lead by frame volume. Other geometrical factors such as particle size and shape were not the same in both investigations. Additional work is planned to determine the relative importance of these variables.

As shown in Figure 2, the slope of the apparent impedance curves at the higher frequencies varies with the percentage of lead by frame volume. This capacitive effect is shown more clearly in Figure 5 where the difference between the apparent impedance at 6,365 cps and that at 20,000 cps is plotted versus the percentage lead by frame volume for a constant porosity of 14.4 percent. The curve has a positive intercept because there is a slight impedance difference between these frequencies for the cores free of lead. The curve indicates that the capacitive

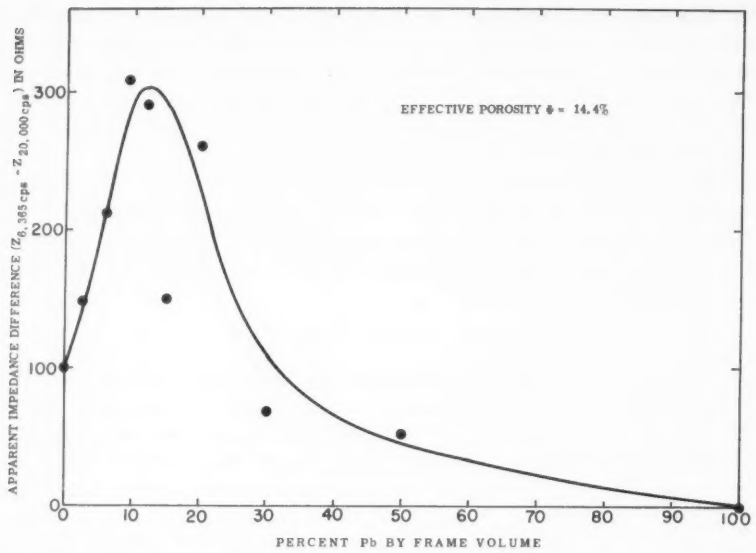

FIG. 5. Apparent impedance difference ($Z_{6,365\ cps} - Z_{20,000\ cps}$) versus percent lead by frame volume for ore with a constant porosity of 14.4 percent.

effect produced in this synthetic ore attained a maximum at 11 percent lead by frame volume.

Figure 6 indicates the changes in the capacitive effect with porosity for a constant lead content by frame volume of 20 percent. As the porosity decreases, the difference between the apparent impedance measured at the two frequencies increases. This increase in the capacitive effect is caused by the increase in the resistivity of the material between the lead spheres. The extent to which small variations in the mean distance between the lead spheres have affected these results has not been established.

Low Frequency Effects

The data of Figure 2 indicate that at low frequencies the normalized apparent impedance of an ore with 12 percent lead by frame volume is greater than that for a core barren of lead, if the saturating fluid and the porosity are the same in both cases. It is believed that this effect maintains itself for lower frequencies than shown on the diagram and even down to zero frequency, or direct-current techniques. This effect for small lead content is tentatively explained as follows: For low frequency or direct-current techniques, only a small portion of the current flows through the conductive spheres. Also, the electric field has probably

been distorted sufficiently to give a net increase in the mean conductive path. The implication of this result is somewhat surprising, for it means that the apparent impedance—and hence apparent resistivity for direct-current techniques—of a porous rock containing small disseminated conductive particles would be *greater* than that of a corresponding barren rock, provided the porosity and saturating fluid were the same in both cases. Because, in direct-current techniques, an apparent resistivity minimum is often observed over disseminated sulphide ore deposits which lie at or near the ground-water table, the conclusion must be—on the basis of the above reasoning—that the observed apparent resistivity minimum is probably usually caused by low-resistivity electrolytes (usually acidic water) rather than the low resistivity of the sulphide particles themselves.

In order to study the divergence in the apparent impedance produced by changes in the current density in the low frequency range (see Figure 2), it was found convenient to define a term designated "polarization index," ΔZ_a, which could be calculated directly from the apparent impedance measured at a constant frequency, (f), and at the two different current densities, J and J/k, respectively, using the following equation

$$(\Delta Z_a)_f = (Z_a)_{J/k} - (Z_a)_J. \tag{4}$$

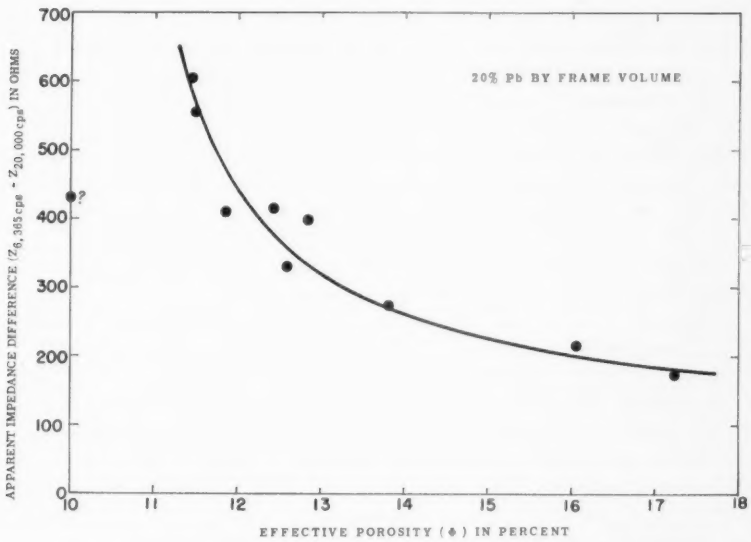

FIG. 6. Apparent impedance difference ($Z_{6,365\ cps}$–$Z_{20,000\ cps}$) versus effective porosity for ore with 20 percent lead by frame volume.

For the particular experiments described in this paper

$$f = 10 \text{ cps}, J = J_1 = 3.51 \times 10^{-4} \text{ amp/cm}^2, \quad \text{and} \quad k = 10.$$

ΔZ_a has been observed to take on positive values throughout this experimental work. In the computation of the polarization index for any given lead content by frame volume, the apparent impedance was not normalized in order that this index would be representative of a given number of lead spheres even though the porosity varied. Due to the method of manufacture of this ore, the core length decreases with decrease in porosity, but the number of lead spheres for a given lead content by frame volume remains nearly constant.[3] Z_a is used to designate unnormalized apparent impedance for a given core, and for any given current density J it can be calculated by multiplying the right-hand side of equation (1) by l_c/A_c.

Referring again to Figure 2, it is observed that at a constant low frequency, the divergence between the J_1 and $J_1/10$ curve is greater for the ore containing 12 percent lead by frame volume than that containing 20 percent lead. This effect is shown quantitatively in Figure 7 where the polarization index is plotted against the percentage of lead by frame volume (0, 3, 6, 9, 12, 15, 20, 50 percent, and solid lead) for a constant frequency of 10 cps and for a constant porosity of 14.4 percent. In the region from zero to 12 percent lead by frame volume (Figure 7), there is a rapid increase in the polarization index due to the small probability of two lead spheres being in contact and acting as a single polarizable unit. For increasing amounts of lead by frame volume, the polarization index attains a maximum at about 15 percent lead by frame volume and then decreases in a linear manner throughout the rest of the plot. This maximum and subsequent decrease in the polarization index are explained by the fact that there is a maximum attainable number of single polarizable units for a given length and porosity of ore specimen. The polarization index for an ore specimen with 50 percent lead by frame volume is the same as one with about 10 percent lead. The most right-hand point on the graph is for a solid lead cylinder of zero porosity whose dimensions were essentially the same as those of the cores.

Figure 8 shows how the polarization index varies with the effective porosity of the synthetic ore for measurements taken at 10 cps. The data are for ore containing 20 percent lead by frame volume. The polarization index increases markedly with decreasing porosity. For example, the polarization index for an effective porosity of 11.4 percent is approximately 10 times the polarization index of a similar ore with 17 percent effective porosity. The apparent cause of this phenomenon is that as the porosity decreases there is an increase in the tortuosity of the ionic paths, and/or a larger percentage of the current passes through the surfaces of the lead spheres.

[3] For example, for a lead content by frame volume of 20 percent, the length of the cores decreased by about 12 percent as the porosity decreased from 18 to 10 percent. However, there was essentially no variation in the length of the cores for a given porosity as the percentage of lead was varied.

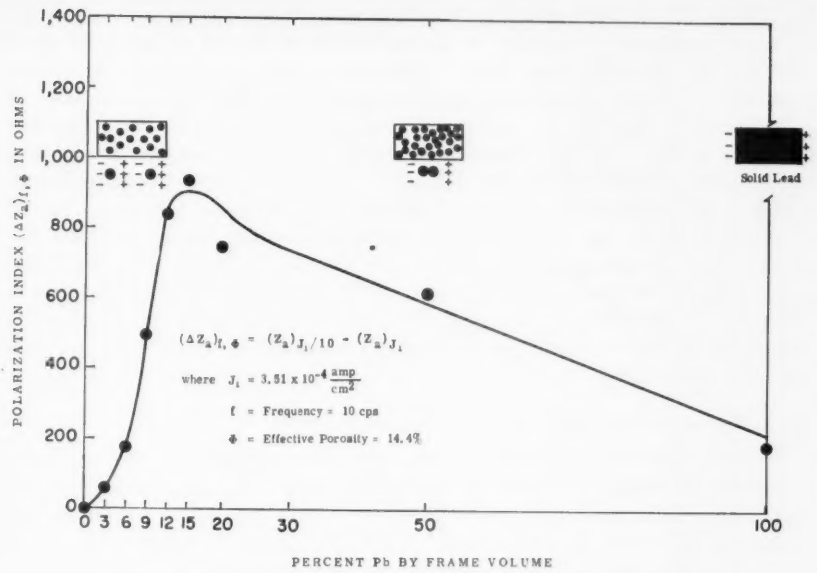

FIG. 7. Polarization index at 10 cps versus percent lead by frame volume for ore with a constant effective porosity of 14.4 percent.

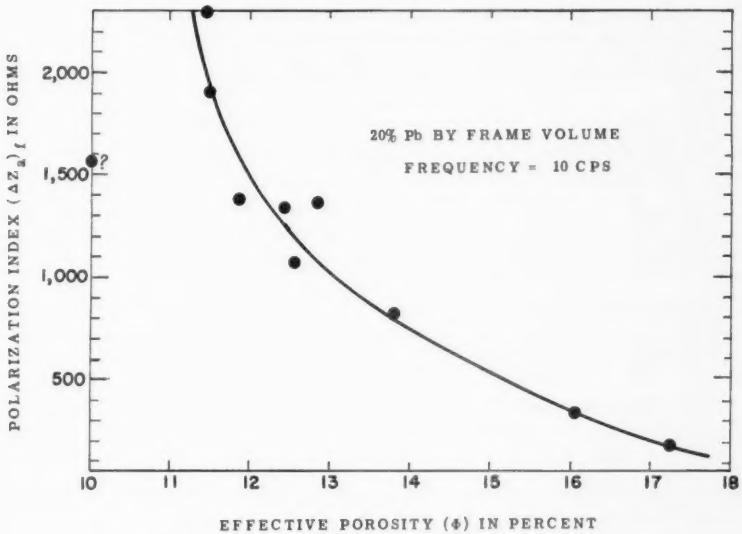

FIG. 8. Polarization index at 10 cps versus effective porosity for ore with 20 percent lead by frame volume.

Although the mechanism that produces the divergence in the normalized apparent impedance with respect to current density in the low frequency range is not completely understood, certain general statements can be made. These polarization effects are produced by physical-chemical phenomena that occur at the boundary zone between the lead spheres and the electrolyte. The magnitude of these effects is intimately controlled by the nature of this boundary zone. These effects are often more pronounced when the surface of the conductor is coated with some intermediate product. These effects are believed to increase as the resistivity of the conductive particle decreases. Finally, these effects are influenced by the ionic potential of the ions in the electrolyte and the composition of the conductive particle. It is not known to what extent divalent lead ions in the electrolyte and the surface condition of the lead spheres, such as the presence of an intermediate product, have affected the amplitude of the divergence discussed in this study.

Correlations Between High and Low Frequency Effects

Figure 9 shows the relation between the low frequency polarization effects and the high frequency capacitive effect. The graph was obtained by plotting, as ordinates, the polarization index at 10 cps versus the differences between the unnormalized apparent impedance at 6,365 cps and that at 20,000 cps, as the abscissas. This plot can be obtained directly from Figures 6 and 8. All points are for cores containing 20 percent lead by frame volume. The distribution of these points is mainly controlled by variations in the effective porosity. The nearly linear relationship as shown on this graph indicates that there are parameters common to both phenomena at a given percentage of lead by frame volume. The important considerations here are the porosities and the constancy of the lead content.

Another correlation between the high and low frequency effects is shown by comparison of Figures 5 and 7. In each of these cases the porosity is held constant at 14.4 percent and the percentage of lead by frame volume is varied. It can be seen that the effects shown on these graphs manifest themselves similarly over the entire range of lead content. In this case the important variable common to both the high and low frequency effects is the lead content.

Synthesis of Polarization Effects

The observed polarization effects of the ore were synthesized in the following manner. First, using a solid lead cylinder, the polarization effects were measured, and an empirical equation was then found which would describe the measured effects. Next, the polarization effects were measured using a sample of synthetic ore. It was found that the same empirical equation approximately fitted both sets of data. This fact implied that the polarization effects were superimposed upon the ohmic impedance of the synthetic ore.

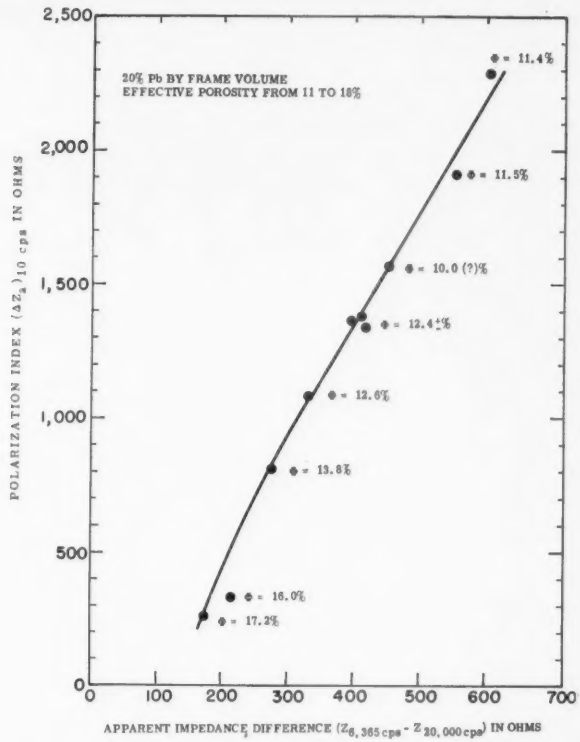

FIG. 9. Polarization index at 10 cps versus apparent impedance difference ($Z_{6.365\ cps}$–$Z_{20,000\ cps}$) for ore with 20 percent lead by frame volume and effective porosities ranging from 11 to 18 percent.

Figure 10 shows how the polarization effects on the faces of a solid lead cylinder affect the normalized apparent impedance of the cylinder as the current density is varied sixfold. These effects are of only moderate amplitude due to the small available surface area at the ends of the lead cylinder as compared with the large available surface area of the lead spheres in the synthetic ore (compare 10 cps curves of Figures 10 and 11). An empirical equation that approximates these data is given by

$$(\mathrm{Z}_a)_{\Phi,J} = \frac{1}{d + hJ} + \mathrm{Z}_\infty \tag{5}$$

where d and h are arbitrary constants, J is the current density, and Z_∞ is the value of the normalized apparent impedance which is obtained by extrapolation to an

infinite current density. The curve of Figure 10 is for values of this equation when $Z_\infty = 63.4$ ohm-cm, $d = 1.64 \times 10^{-4}$ mho/cm, and $h = 10.08$ cm/volt. This equation was adopted as representative of the polarization effects of lead. According to this equation, the polarization effects are given by the first term on the right-hand side of equation (5), which approaches zero as the current density, J, becomes infinitely large. Z_∞ can be thought of as the normalized ohmic impedance upon which polarization effects are superimposed. At a given frequency, the maximum possible value of this superimposed impedance is given by the factor $1/d$.

Figure 11 shows a series of plots of the normalized apparent impedance versus current density for a core having 12 percent lead by frame volume and with an effective porosity of 13.8 percent. The data were obtained for frequencies of 10, 37, 51, 71, and 100 cps. The curves, which were computed from equation (5), fit the observed data very well. In using equation (5), the arbitrary constants d and h for each frequency were determined from the observed values of the normalized apparent impedance, but no attempt has yet been made to relate these constants to the properties of the synthetic ore.

Figure 12 is a plot of the normalized apparent impedance in thousands of ohm-centimeters versus frequency. This plot shows the limiting values of the normalized apparent impedance as deduced from equation (5) fitted to the data given in Figure 11. The curve labeled $J = 0$, which shows the normalized apparent

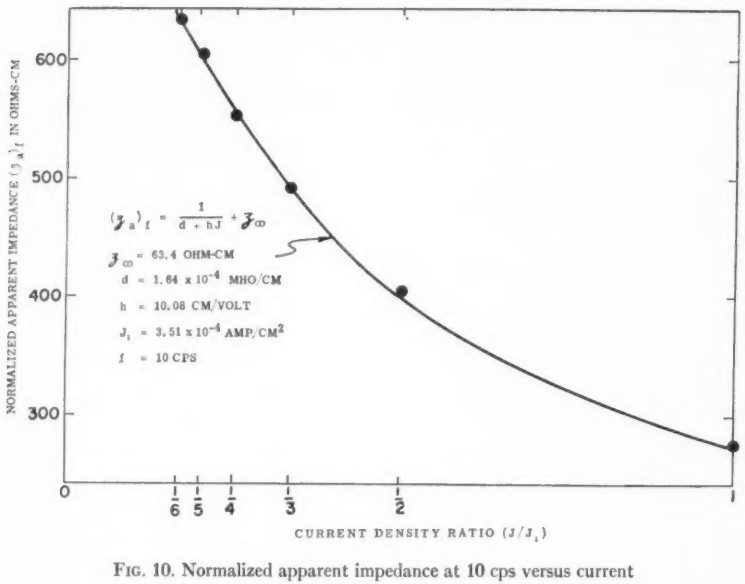

FIG. 10. Normalized apparent impedance at 10 cps versus current density ratio J/J_1 for solid lead cylinder.

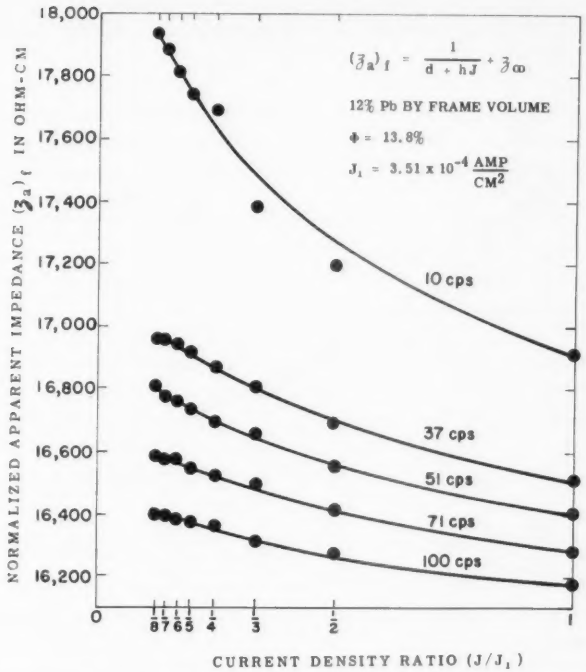

FIG. 11. Normalized apparent impedance versus current density ratio J/J_1 for ore sample with 12 percent lead by frame volume and effective porosity of 13.8 percent. Data taken using frequencies 10, 37, 51, 71, and 100 cps.

impedance for zero current density, can be thought of as the largest possible value that the normalized apparent impedance can attain at any particular frequency. The curve labeled $J = \infty$, which shows the normalized apparent impedance at infinite current density—that is, the case in which the polarization effects have been completely overridden—is postulated to be the normalized ohmic impedance of the synthetic ore. The two intermediate curves represent the upper $(J_1/8)$ and lower (J_1) bounds of the measured effects shown in Figure 11.[4] The curve for infinite current density is the curve which should be considered when attempts are made to establish equivalent circuits for ohmic conduction through such synthetic ore.

Figure 13 shows a simple equivalent circuit which agrees with the experimental observations given above. C_m is the normalized capacitance between the metal spheres, and it ranges from zero to several hundred micro-micro farads per centi-

[4] For the current density J_1 there is a discrepancy between the curves in Figures 2 and 12 because the resistivities of the saturating electrolytes were different for the two sets of data.

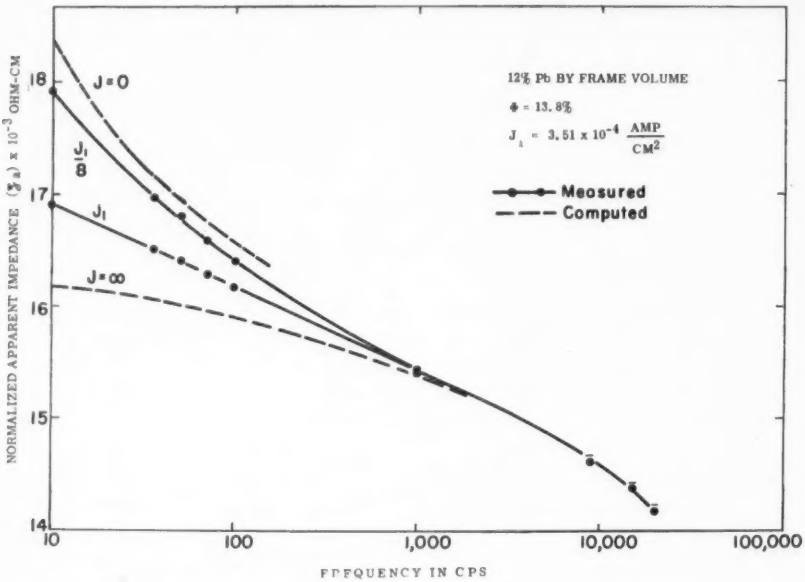

FIG. 12. Normalized apparent impedance versus frequency for ore sample with 12 percent lead by frame volume and effective porosity of 13.8 percent. Curves show postulated limiting values of normalized apparent impedance with current density.

meter. R_m is the normalized resistance (resistivity) of the metal which, in this case, is extremely small. γR_e is the component of the normalized resistance produced by the electrolytic paths in parallel with the normalized capacitance C_m,

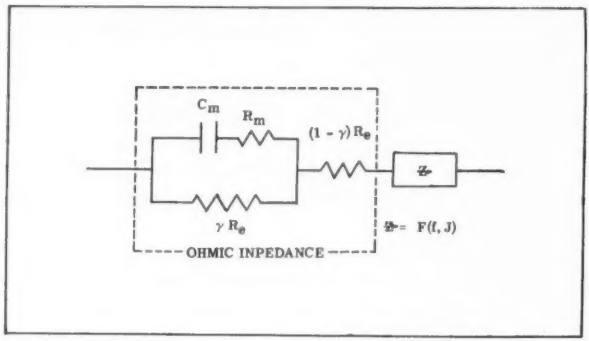

FIG. 13. Equivalent circuit based on experimental results.

and varies from zero to a few thousand ohm-centimeters. $(1-\gamma)R_e$ is the additive component of the normalized resistance produced by the electrolytic paths, and varies from a few hundred ohm-centimeters to the order of ten thousand ohm-centimeters. $\bar{Z}$ is the non-linear portion of the over-all normalized apparent impedance which, for a given sample, is a function of frequency and current density, and varies from zero to a few thousand ohm-centimeters.

CONCLUSIONS

The electrical properties of a synthetic ore containing lead are different from those for a corresponding core barren of lead. For cores barren of lead, there is essentially no variation in the normalized apparent impedance with respect to either frequency or current density. For ore containing lead, there is a significant variation of the normalized apparent impedance with frequency and with current density when the frequency is below approximately 5,000 cps. The polarization effects apparently manifest themselves so as to be superimposed upon the normalized ohmic impedance of a given sample of synthetic ore. The normalized ohmic impedance is approached as the current density tends toward an infinitely large value.

High frequency considerations

1. The normalized apparent impedance is essentially independent of current density for frequencies above approximately 5,000 cps whether or not the samples contain lead.

2. For cores used in this research, the data show that at a constant frequency above that at which the normalized apparent impedance is dependent on current density and for a constant amount of lead by frame volume, a relationship which is similar in form to Archie's law exists between the normalized apparent impedance and the effective porosity.

3. When the normalized apparent impedance, taken at 6,365 cps, is plotted against the percentage of lead by frame volume, anomalous values of normalized apparent impedance occur such as to give, for these data, a maximum in the region of 4 percent lead by frame volume. The magnitude of this anomalous effect increases with decreasing porosity, in the range (10 to 20 percent) of porosities used.

4. When lead was included in the frame of a core, the capacitive effect was dependent upon the amount of lead in the core and upon the porosity of the core.

Low frequency considerations

1. For low frequency or direct-current techniques and using synthetic ore containing less than 12 percent lead by frame volume, only a small portion of the current flows through the small disseminated conductive particles; moreover, these particles distort the electric field sufficiently to give a net increase in the mean conductive path. This effect causes the normalized apparent impedance

to increase above that of a corresponding barren rock, provided that all other variables remain the same.

2. For a core containing lead, at a constant frequency below 5,000 cps, the normalized apparent impedance varies with current density in such a way as to produce a maximum value of normalized apparent impedance as the current density tends toward zero, and to approach a minimum value of normalized apparent impedance as the current density tends toward an infinitely large value.

3. For frequencies below approximately 5,000 cps, the variation of normalized apparent impedance with current density is dependent on the amount of lead in the cores. For the experimental conditions such as described in this paper, the maximum variation at 10 cps occurred at approximately 15 percent lead by frame volume.

4. For frequencies below approximately 5,000 cps, the variation of normalized apparent impedance with current density is dependent on the effective porosity of the synthetic ore containing lead. For the experimental conditions described in this paper, the polarization index increased markedly with decreasing porosity.

Correlations between high and low frequency effects

There is a nearly linear relationship between the capacitive effect at frequencies above approximately 5,000 cps and the impedance variations with current density at 10 cps, namely the polarization index. The variables common to both effects are the porosity and the lead content.

ACKNOWLEDGMENTS

Acknowledgment is given to David L. Bean and Thomas A. Morgan for assistance in the laboratory and computational work. The project was supported by funds from the Kennecott Copper Company Research Fund of the College of Mines and Mineral Industries, University of Utah, and from the University of Utah Research Fund.

APPENDIX

Figure 14 indicates the nature of the approximation upon which equation (1) is based. The relative magnitudes of the vectors and the phase angles have been modified to aid the explanation. Vector $\overrightarrow{Z_{ci}}$ represents the impedance of the measurement cell with the saturated core in place and with the two ends filled with electrolyte of resistivity $\overrightarrow{\rho_e}$. Vector $\overrightarrow{Z_{co}}$ represents the impedance of the measurement cell when the core is out and the cell is completely filled with electrolyte of resistivity $\overrightarrow{\rho_e}$. The impedance of the system in series with the core is given by

$$\overrightarrow{Z_{co}} - \overrightarrow{\rho_e}\left(\frac{l_c}{A_c}\right), \quad \text{where} \quad \overrightarrow{\rho_e}\left(\frac{l_c}{A_c}\right)$$

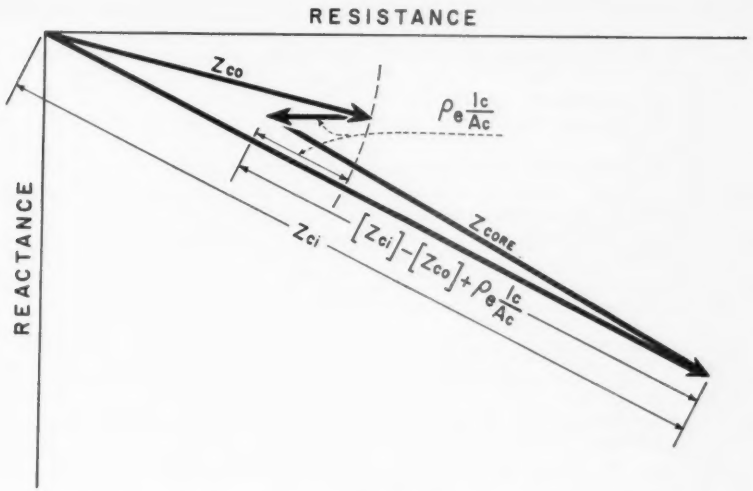

FIG. 14. Plot of reactance versus resistance showing the approximation used in the development of equation (1).

is the resistance of a volume of the electrolyte having the same shape and orientation as the particular core being measured. The impedance of the core is therefore given by the vector equation

$$\vec{Z}_{core} = \vec{Z}_{ci} - \left(\vec{Z}_{co} - \vec{\rho}_e \frac{l_c}{A_c}\right), \tag{6}$$

which can be approximated, for small phase angle differences, by the scalar equation

$$Z_{core} = Z_{ci} - Z_{co} + \rho_e \frac{l_c}{A_c} \cdot \tag{7}$$

Normalization by the geometric factor (A_c/l_c) gives the impedance per unit length of the core which in this paper is referred to as the normalized apparent impedance

$$Z_a = Z_{core}\left(\frac{A_c}{l_c}\right) = (Z_{ci} - Z_{co})\frac{A_c}{l_c} + \rho_e \cdot \tag{1}$$

Additional experiments in which phase shift was taken into account have shown that this approximation produces errors which are small.

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GEOPHYSICS, VOL. XXIV, NO. 3 (JULY, 1959), PP. 531–546, 12 FIGS.

UNIQUE DETERMINATION OF CONDUCTIVITY, SUSCEPTIBILITY, SIZE, AND DEPTH IN MULTIFREQUENCY ELECTROMAGNETIC EXPLORATION*

STANLEY H. WARD†

ABSTRACT

The response of a conductive, magnetic sphere in a uniform, alternating magnetic field is a function of the conductivity, permeability, and radius of the sphere and of the frequency of the alternations. Over one range of frequencies, eddy-current density in any given sphere and secondary magnetic fields of the sphere are relatively constant and high. Over a much lower range of frequencies eddy currents are negligible, but the secondary magnetic fields may be of large constant amplitude but of polarity reversed to that of the higher frequency range. At some intermediate frequency the secondary magnetic fields will be entirely quadrature with respect to the inducing field.

Utilization of this peculiar frequency dependence and of the geometry of the secondary magnetic fields permits unique determination of the conductivity, permeability, radius, and depth to the center of a buried sphere. The procedure for obtaining these variables is described in this article.

As an added feature, it is shown that by completing a gravity survey as well as an electromagnetic survey over a dense, magnetic, conductive spherical ore body, it is possible to determine the above variables, plus density, uniquely. Precise identification of the material of the sphere is seen as a possible result of the application of this technique.

INTRODUCTION

The fact that the interpretation of anomalies in any of the potential fields is incapable of a unique solution has been mentioned repeatedly in the geophysical literature (Nettleton, 1940; Skeels, 1947 and 1949; Garland, 1951). As Garland states it, "For any given anomaly there is in reality a double infinity of possible solutions. First, the anomalous property of the unknown body is given only by certain limits, and, secondly, for any particular property value, there remains an infinite number of forms and positions which the body could have." That such is not necessarily the case with nonpotential fields is demonstrated below. It is shown that it is possible to derive uniquely the depth, the radius, the electrical conductivity, and the magnetic susceptibility of a hidden spherical body from analysis of multifrequency electromagnetic survey data.

THEORETICAL ANALYSIS

Slichter (1932) and Wait (1951) have shown theoretical response curves for a conducting sphere in a uniform field. Both these authors limited discussion to the problem of a sphere whose permeability (and the permeability of its surroundings) was that of free space. The introductory mathematical development by Wait involves an arbitrary permeability contrast between sphere and surroundings. In a subsequent paper, Wait (1953) presented the complete solution of the problem of a sphere of arbitrary permeability and conductivity in a dipolar field.

For a sphere in a uniform field, as illustrated in Figure 1, Wait (1951) de-

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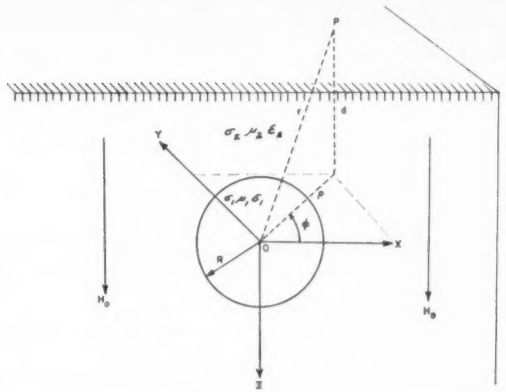

FIG. 1. Geometrical relationships for a conducting permeable sphere in a uniform alternating magnetic field.

veloped the following formulas:

$$H_z(\omega) = -\frac{3}{2} R^3 H_o(M + iN)\left(-\frac{1}{r^3} + \frac{3z^2}{r^5}\right), \tag{2}$$

$$H_\rho(\omega) = -\frac{3}{2} R^3 H_o(M + iN)\frac{3z\rho}{r^5}, \tag{3}$$

$$M + iN = -\frac{2}{3}\left[\frac{2\mu_1(\sinh\alpha - \alpha\cosh\alpha) + \mu_2(\sinh\alpha - \alpha\cosh\alpha + \alpha^2\sinh\alpha)}{2\mu_1(\sinh\alpha - \alpha\cosh\alpha) - 2\mu_2(\sinh\alpha - \alpha\cosh\alpha + \alpha^2\sinh\alpha)}\right], \tag{4}$$

where

$$\alpha = (i\sigma_1\mu_1\omega - \epsilon_1\mu_1\omega^2)^{1/2}R, \tag{5}$$

and

σ_1 = conductivity of sphere in mhos/meter,
μ_1 = permeability of sphere in henrys/meter,
ϵ_1 = permittivity of sphere in farads/meter,
ω = angular frequency of source field,
H_o = magnitude of applied uniform field in ampere-turns/meter,
μ_2 = permeability of surrounding medium in henrys/meter,
R = radius of sphere in meters.

The center of the sphere is taken as the origin of the spherical polar coordinate system. The polar axis is taken parallel to the applied field. It has been assumed also that $|\gamma_2 R| \ll 1$, where γ_2 is the propagation constant of the external medium

$$[\gamma_2 = (i\sigma_2\mu_2\omega - \epsilon_2\mu_2\omega^2)^{1/2}],$$

and that there is no restriction on the parameter $|\gamma_1 R|$, where

$$\gamma_1 = \{i\sigma_1\mu_1\omega - \epsilon_1\mu_1\omega^2\}^{1/2}.$$

The z-component of the field of a dipole oriented in the Z-direction is written in cylindrical co-ordinates

$$H_z(\omega) = \frac{P}{4\pi}\left[-\frac{1}{r^3} + \frac{3Z^2}{r^5}\right], \tag{6}$$

so we may consider the quantity

$$P = -\frac{3}{2} R^3 H_o(M + iN) \times 4\pi \tag{7}$$

as the equivalent dipole moment of the sphere. The in-phase component M and the quadrature component N are plotted, in Figure 2, versus the dimensionless parameter θ given by $\theta = (\sigma_1\mu_1\omega)^{1/2}R$. In calculating these curves, displacement currents have been assumed negligible, i.e., $\epsilon_1\omega \ll \sigma_1$, and all permeabilities assumed to be those of free space, i.e., $\mu_1 = \mu_2 = \mu_0 = 4\pi \times 10^{-7}$ henrys/meter.

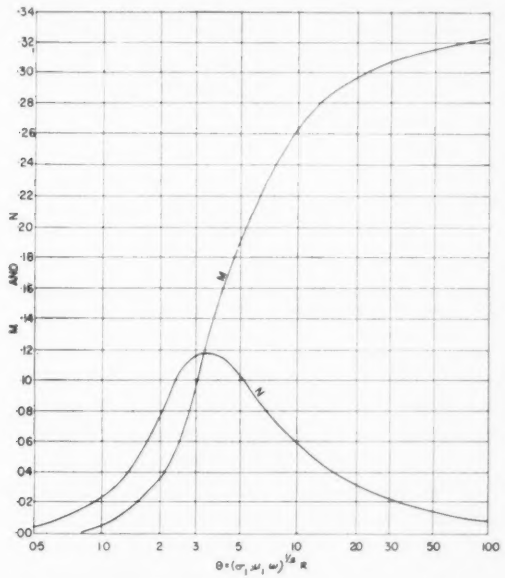

FIG. 2. In-phase and out-of-phase components of induced dipole moment of a conducting sphere in a uniform field.

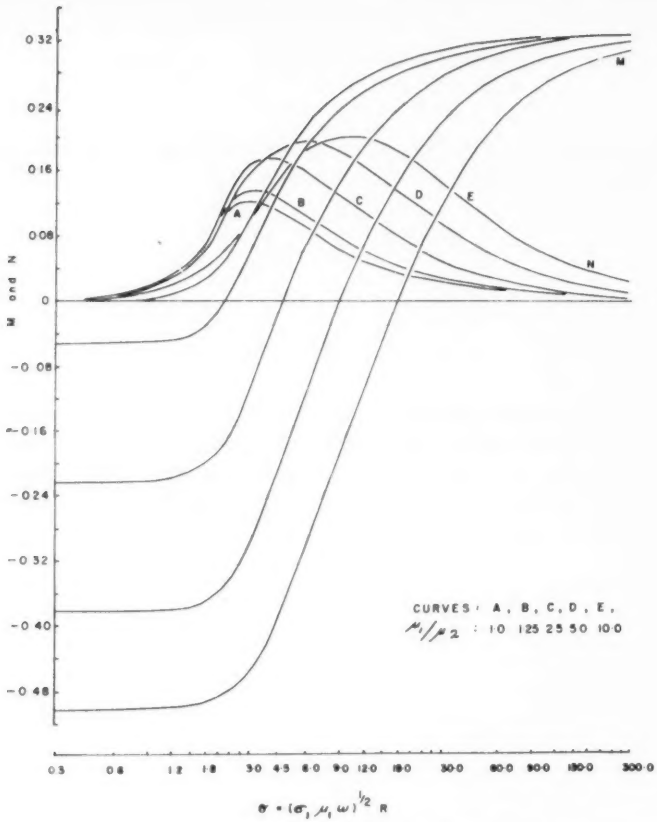

FIG. 3. In-phase and out-of-phase components of induced dipole moment of a conducting, permeable sphere in a uniform field for various values of permeability contrast.

Of a more general nature are the magnetic fields for arbitrary values of the permeability ratio μ_1/μ_2. The calculations of M and N pertaining to this case have been carried out for five values of μ_1/μ_2 by the author and the results presented graphically in Figures 3, 4, and 5. The response curves for $\mu_1 = 5.0\mu_2$ or $\mu_1 = 10.0\mu_2$ could apply to a spherical body of massive magnetite in a relatively non magnetic rock, while those for $\mu_1 = 1.25\mu_2$ could apply to a spherical pyrrhotite body in a similar rock. The permeability contrast μ_1/μ_2 is assumed to be independent of field strength. This seems to be a reasonable assumption, since the field strengths involved are quite small. Heiland (1946) shows hysteresis and susceptibility curves for a sample of magnetite which suggests that only the

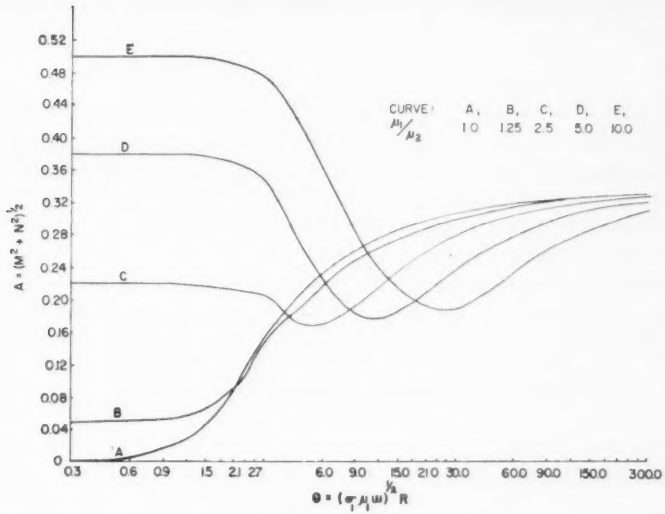

FIG. 4. Amplitude of induced dipole moment of a conducting, permeable sphere in a uniform field for various values of permeability contrast.

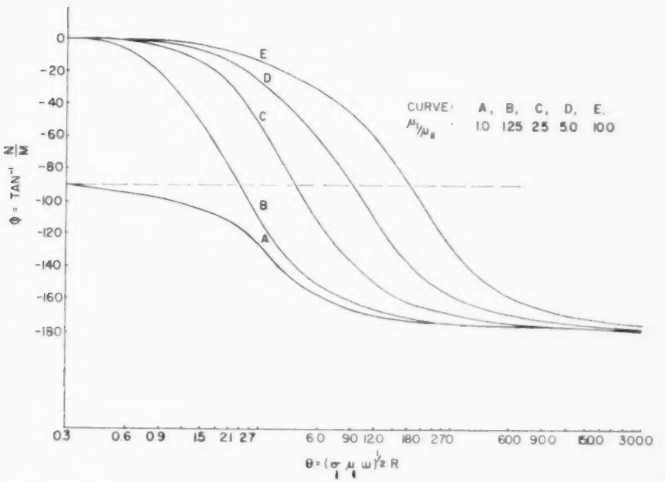

FIG. 5. Phase of induced dipole moment of a conducting, permeable sphere in a uniform field for various values of permeability contrast.

initial susceptibility need be considered for field strengths up to 10 ampere-turns/meter.

UNIQUE DETERMINATION OF VARIABLES

It is readily seen from Figure 3 that there is some critical angular frequency ω_c at which any magnetic conducting sphere has zero in-phase response. This critical frequency, dependent upon the permeability, the conductivity, and the radius of the sphere, separates the regions in which the induced dipole moment is positive (permeability the predominating physical property) and negative (conductivity the predominating physical property).

This type of response suggests that one instrument might be developed to serve as both an induction magnetometer for locating magnetic bodies and as an eddy-current inductor for locating conducting bodies. Where a geological mass has both high conductivity and high permeability, then a definite correlation between the magnetic and electromagnetic methods is indicated.

Determination of Depth

The depth d may be obtained readily. Note that

$$H_\rho(\omega) = \frac{P}{4\pi} \frac{3z\rho}{r^5} . \tag{8}$$

This function has a maximum and a minimum, for the case when the depth $z=d=$constant, at $\rho=\pm d/2$. Hence, analysis of a curve showing $H_\rho(\omega)$ plotted versus ρ for $y=0$ will give d (Figure 6).

Determination of Permeability

It is of interest to note that the permeability contrast between a hidden spherical body and the surrounding medium may be found without any knowledge of the true location, size, or conductivity of the sphere. To obtain μ_1/μ_2, all that is required is the application of a uniform harmonically-varying field and measurement of the induced field at one point in space for frequencies ranging from very low to very high on either side of the critical frequency.

It may be shown from equations (4) and (7) that the induced dipole moment of a sphere when no eddy currents flow ("zero eddy-current response") is

$$P^0 = \frac{\mu_1 - \mu_2}{\mu_1 + 2\mu_2} H_o R^3 \times 4\pi \tag{9}$$

(a positive dipole moment). This expression is representative of the response of a sphere at any frequency if the conductivity is zero, or it represents response extrapolated to zero frequency if the conductivity is finite. Thus, from equation (3),

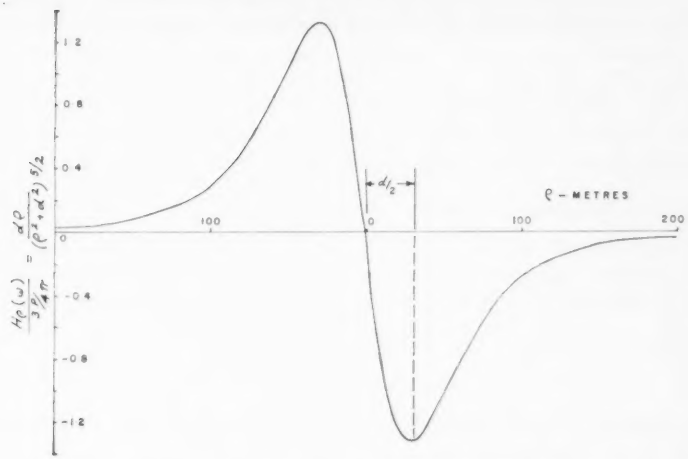

FIG. 6. Obtaining depth d to the center of a sphere from the plot of $H\rho(\omega)$ versus horizontal distance Z for traverse over sphere.

$$H_\rho(0) = \frac{\mu_1 - \mu_2}{\mu_1 + 2\mu_2} H_o R^3 \frac{3z\rho}{r^5} . \tag{10}$$

Similarly, the induced dipole moment of a sphere when eddy-current density is a maximum ("maximum eddy-current response") is

$$P^\infty = -\frac{H_o R^3}{2} \times 4\pi \tag{11}$$

(a negative dipole moment). This expression represents the response of a sphere of finite conductivity extrapolated to infinite frequency. Note that $M \rightarrow \frac{1}{3}$ and $N \rightarrow 0$ as $\omega \rightarrow \infty$ in equation (4). Again, from equation (3),

$$H_\rho(\infty) = -\frac{H_o R^3}{2} \frac{3z\rho}{r^5} . \tag{12}$$

$H_\rho(\infty)$ has the opposite sign to that of $H_\rho(0)$. If the ratio of $H_\rho(0)$ to $H_\rho(\infty)$ [or $H_Z(0)$ to $H_Z(\infty)$ for that matter] is measured at any point in space, the permeability ratio μ_1/μ_2 is uniquely determined, for

$$\frac{H_\rho(0)}{H_\rho(\infty)} = \frac{\text{response extrapolated to zero frequency}}{\text{response extrapolated to infinite frequency}},$$

$$= \frac{P^0}{P^\infty} = \frac{M^0}{M^\infty} = -2\left[\frac{\mu_1/\mu_2 - 1}{\mu_1/\mu_2 + 2}\right]. \tag{13}$$

This equation has been used to plot the curve of Figure 7.

Thus the frequency is varied until the transition is complete from zero eddy-current response to essentially maximum eddy-current response and the ratio of the secondary field at the two extremes is recorded; the permeability contrast μ_1/μ_2 is then obtained from Figure 7. Either the $H_Z(\omega)$- or the $H_\rho(\omega)$-component could be measured for this purpose. It is not necessary to have the measuring device calibrated in terms of field strength, since only a ratio is required.

Determination of Radius of Sphere

Having obtained the depth to the center of the sphere and the permeability contrast between the sphere and its surroundings, it is comparatively easy to obtain the radius R of the sphere. From equation (10), it is found that

$$R^3 = \frac{H_\rho(0)}{H_o} \frac{\mu_1 + 2\mu_2}{\mu_1 - \mu_2} \frac{(d^2 + \rho^2)^{5/2}}{3\rho d} \tag{14}$$

for any point on the earth's surface. The sign of $H_\rho(0)$ is such as to give a positive value to R. From equation (12),

$$R^3 = -\frac{H_\rho(\infty)}{H_o} \frac{2(d^2 + \rho^2)^{5/2}}{3\rho d}$$

for the same point.

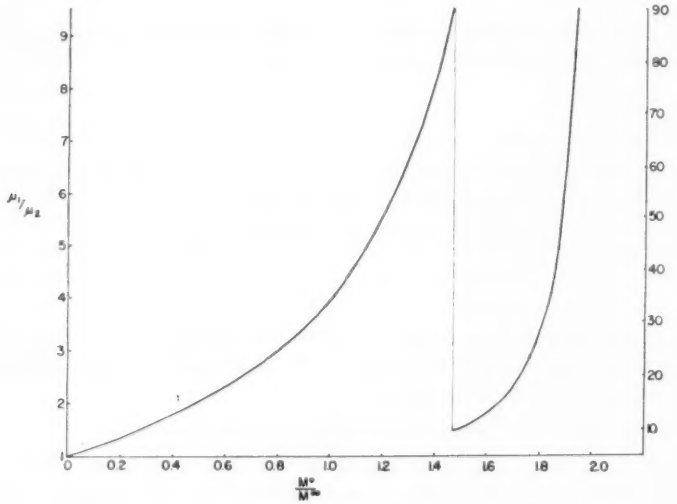

FIG. 7. Obtaining permeability contrast μ_1/μ_2 of a sphere from the ratio

$$\frac{M^0}{M^\infty} = \frac{H_\rho(0)}{H_\rho(\infty)} = \frac{\text{response extrapolated to zero frequency}}{\text{response extrapolated to infinite frequency}}.$$

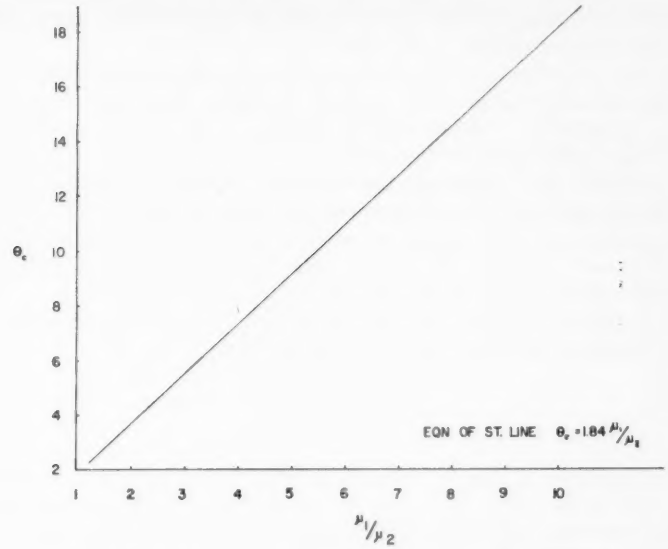

FIG. 8. Critical frequency θ_c versus permeability contrast μ_1/μ_2 for a conductive, permeable sphere.

$H_\rho(\infty)$ has the opposite sign to that which $H_\rho(0)$ had in the previous solution. Either equation (14) or (15) may be used to calculate the radius of the sphere when the ratio $H_\rho(\omega)/H_o$ is measured at the point (ρ, d), and d is obtained from a profile such as given in Figure 6.

Determination of Conductivity

The conductivity of the sphere may be found next. The value of the dimensionless parameter $\theta = (\sigma_1\mu_1\omega)^{1/2}R$ will be known at, for example, the critical frequency ω_c; the appropriate response curve corresponding to the determined μ_1/μ_2 value is chosen from the universal set of curves of Figure 3. To avoid the necessity of interpolation between curves if μ_1/μ_2 is other than one of the values for which complete response curves are plotted in this figure, a curve of the critical value θ_c vs. μ_1/μ_2 is presented in Figure 8. It is usually possible to estimate or readily to measure μ_2, and, hence, knowing μ_1/μ_2 we can obtain μ_1. Since R and μ_1 are now known, σ_1 may be calculated.

Summary

If remanent magnetic effects are neglected, P^0 may be obtained from a normal magnetometer survey rather than from the response extrapolated to zero frequency. However, to reduce the effect of remanent magnetism and to insure that

effectively zero frequency and infinite frequency responses are being considered, several frequencies should be employed.

Thus, for a hidden spherical ore body possessing high susceptibility and fairly good conductivity, it is possible to obtain the radius, depth and location of the center, conductivity, and permeability contrast from magnetic field measurements made at the surface of the earth.

If the body only moderately approximates a sphere, then the analysis provides the physical property and geometry factors of an "equivalent" sphere. For bodies which may not be approximated by a spherical shape, the analysis is not valid. The surface distribution of the magnetic field vectors will suggest whether or not the sphere theory is a fair approximation.

If the sphere effectively has zero conductivity, then the location and depth may be found as above. In addition, the product

$$\left(\frac{\mu_1 - \mu_2}{\mu_1 + 2\mu_2}\right) R^3$$

may be evaluated. A complete determination of all variables is not possible. In this case, an advantage arises in measuring harmonically-varying magnetic fields rather than static fields. This advantage is that remanent magnetization has relatively little effect.

EXTENSION OF THEORY TO BODIES OF ARBITRARY SHAPES AND FIELDS OF OTHER FORMS

March (1953) has developed a solution for a conducting sphere in a *dipolar* field and the theory was shown by Robinson (1949) to be consistent with empirical results. March considered zero permeability contrast only. His mathematical development has been extended by the author to include arbitrary permeability contrast, and it is found that for a source magnetic dipole oriented transverse to a radius of the sphere (see Figure 9) the magnetic fields may be written:

$$H_r = \cos\phi \sin\theta \frac{R^3}{b^3 r^3}\left[\frac{-m}{4\pi}\right]\left[D_1 + 6D_2\frac{R^2}{br}\cos\theta + \frac{9}{2}D_3\frac{R^4}{b^2r^2}(5\cos^2\theta - 1) + \cdots\right], \quad (16)$$

$$H_\theta = -\cos\phi \frac{R^3}{2b^3 r^3}\left[\frac{-m}{4\pi}\right]\left[D_1\cos\theta + 4D_2\frac{R^2}{br}(2\cos^2\theta - 1) + \frac{9}{4}D_3\frac{R^4}{b^2r^2}(15\cos^2\theta - 11)\cos\theta + \cdots\right], \quad (17)$$

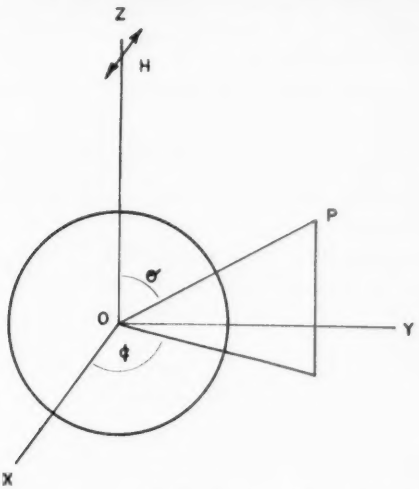

FIG. 9. Orientation of transverse dipole H, relative to sphere, point of observation P, and co-ordinate system employed for equations (16)–(19) inclusive.

$$H_\phi = \sin\phi \frac{R^3}{2b^3r^3}\left[\frac{-m}{4\pi}\right]\left[D_1 + 4D_2\frac{R^2}{br}\cos\theta + \frac{9}{4}D_3\frac{R^4}{b^2r^2}(5\cos^2\theta - 1 + \cdots\right], \quad (18)$$

where

$$D_n = \frac{1 - \dfrac{n+1}{k_1R}\dfrac{\mu_i}{\mu_a}\dfrac{\phi_n(k_iR)}{\phi'_n(k_iR)}}{1 - \dfrac{n}{k_iR}\dfrac{\mu_i}{\mu_a}\dfrac{\phi_n(k_iR)}{\phi'_n(k_iR)}}, \quad (19)$$

$$\phi_n(k_iR) = \frac{(\pi k_iR)^{1/2}}{2}J_n + \frac{1}{2}(k_iR),$$

$$k_iR = R\sqrt{\sigma_i\mu_i\omega}\, e^{-i\pi/4},$$

and

R = radius of the sphere in meters,
b = distance between dipole and center of sphere in meters,
σ_i = conductivity of the sphere in mhos/meter,
ω = angular frequency of source,

μ_i = permeability of sphere in henrys/meter,

μ_a = permeability of surrounding medium in henrys/meter,

$J_{n+1/2}(k_iR)$ = Bessel function of order $n+\frac{1}{2}$,

m = scalar dipole moment of source (= NAI weber-meters for a coil carrying current).

Spherical co-ordinates are employed with the origin taken at the center of the sphere. The restricting conditions imposed are that the wave length in the external medium is much greater than the radius of the sphere and that displacement currents are negligible.

The infinite series appearing in these expressions for the field components can be interpreted in terms of magnetic multipoles located at the origin. In particular, the first term represents an induced dipole moment $P/4\pi$, where

$$\begin{aligned} P &= -\frac{1}{2}\frac{m}{4\pi b^3} R^3 D_1 \times 4\pi, \\ &= -\frac{H_o R^3}{2} D_1 \times 4\pi, \end{aligned} \tag{20}$$

and where

$$H_o = \frac{m}{4\pi b^3}$$

is the field at the origin due to the source dipole when the sphere is removed. This corresponds with the dipole moment

$$P = -\frac{H_o R^3}{2} 3(M + iN) \times 4\pi \tag{21}$$

for the sphere in the uniform field as previously discussed. Hence $D_1 = 3(M_1 + iN_1)$ is seen to be an identity when $b \gg R$ and $r \gg R$ in equations (16), (17), and (18), the fields throughout the region occupied by the sphere then being essentially uniform. The rapid convergence of the infinite series is essential if application of the field formulas is to be practical. This infers that, except for very small values of θ, the ratio R^2/br must be much less than unity.

The above discussion then shows that the unique determination of electrical properties, size, and depth of a sphere may be obtained, to a first approximation, even though the source field is dipolar rather than uniform. To make this approximation valid, the source should be kept well away from the conducting sphere.

The higher multipole terms derived from equation (19), $D_2 = 3(M_2 + iN_2)$, $D_3(M_3 + iN_3)$, and $D_4(M_4 + iN_4)$ for $\mu_1/\mu_2 = 1$ have been calculated by the Computation Center of the University of Toronto. These quantities are plotted as functions of k_iR in Figures 10, 11, and 12.

These terms, of interest when the sphere is close to the dipolar source, are simi-

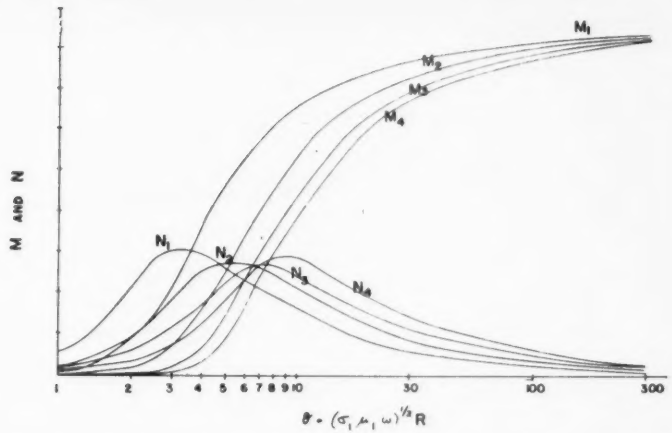

FIG. 10. Variation of in-phase and quadrature components of induced multipole moments as functions of the frequency and of conductivity, permeability, and radius of a sphere in a dipolar field.

lar in behavior to the induced dipole. The summation of all of the multipole terms defines the secondary field of the sphere which then has a phase and magnitude nonlinearly dependent upon the dimensionless parameter $\theta=(\sigma\mu\omega)^{1/2}R$.

Unfortunately, the analysis presented above can seldom be applied exactly in mining geophysics. Complexities in shapes and physical properties of ore

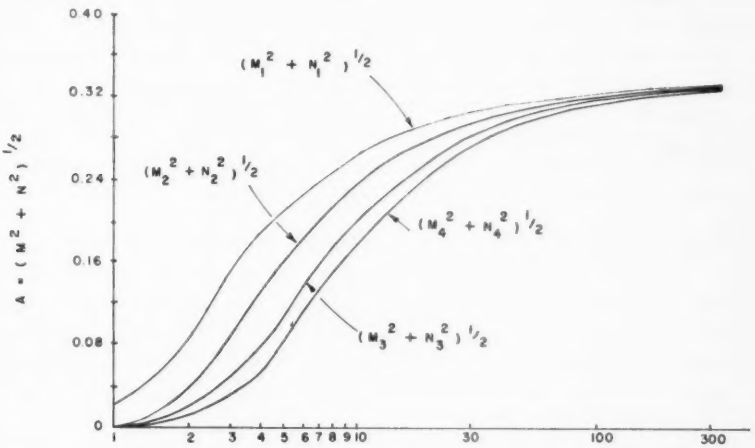

FIG. 11. Variation of amplitude of induced multipole moments as functions of the frequency and of conductivity, permeability, and radius of a sphere in a dipolar field.

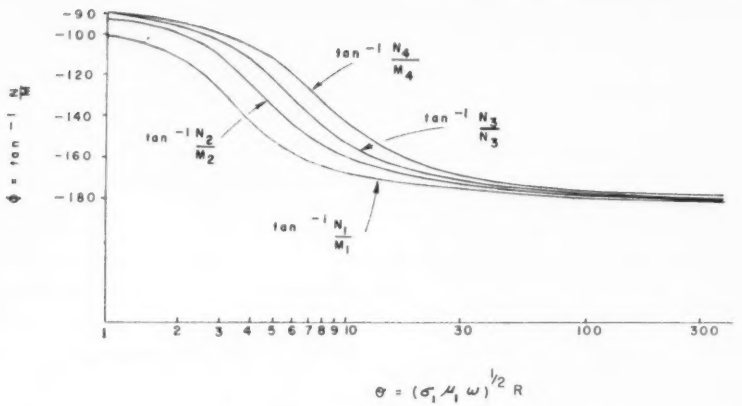

FIG. 12. Variation of phase of induced multipole moments as functions of the frequency and of conductivity, permeability, and radius of a sphere in a dipolar field.

bodies necessitate cumbersome, if not impossible, mathematical models. Intuitively it appears that one could represent any ore body in a dipolar field by a series of magnetic multipoles; the centers of the multipoles would not necessarily be coincident. It is thus considered that any ore body would eventually reach "eddy-current saturation" as the frequency of the energizing source was increased. There is no reason to believe that the frequency of approximate saturation would differ greatly with the shape of the ore body, provided size is maintained sensibly constant.

It is possible to compare results of field tests with results obtained with model ore bodies in the laboratory. The pertinent physical properties and the geometry can then be obtained in this manner by synthesis rather than by analysis as suggested above. The above analysis then serves to prove only that it is possible to obtain all the required data to make a unique physical interpretation of exploration data.

EXTENSION TO INCLUDE COMBINED ANALYSIS OF GRAVITY, MAGNETIC, AND ELECTROMAGNETIC DATA

Garland (1951) shows that without any assumptions about form or position of the hidden body, it is possible to determine the factor k/D, where k = anomalous susceptibility of the body and D = anomalous density of the body. Since it is possible to determine k uniquely from the electromagnetic data for the case of a sphere, obviously the density can be determined uniquely.

In the foregoing section the applied electromagnetic field was assumed to be vertical. Thus the relation between the zero-frequency electromagnetic case and

the gravity anomaly is readily calculated. The vertical magnetic field in the plane $y=0$ is

$$H_z(0) = \frac{\mu_1 - \mu_2}{\mu_1 + 2\mu_2} H_o R^3 \frac{2z^2 - x^2}{r^5},$$

and the gravitational attraction of this sphere in the plane $y=0$ is

$$g_z = Gm \frac{z}{(z^2 + x^2)^{3/2}},$$

where G is the universal constant of gravitation in *mks* units, and hence

$$\frac{\partial g_z}{\partial z} = Gm \frac{2z^2 - x^2}{r^5}$$

and

$$H_z(0) = \frac{\mu_1 - \mu_2}{\mu_1 + 2\mu_2} \cdot H_o R^3 \cdot \frac{\partial g_z}{\partial z} \cdot \frac{1}{Gm}.$$

By measuring $H_Z(0)$, H_o, and g_Z, at any point in the $y=0$ plane, knowing G, calculating μ_1/μ_2 and R^3, then D may be determined uniquely. Thus combined electromagnetic and gravity surveys theoretically could lead to a complete specification of the three physical properties: magnetic permeability, electrical conductivity, and density. Knowledge of these properties for any one body often is sufficient for unique determination of the nature of the material constituting the body.

CONCLUSION

Practical application of the analysis presented herein may be made in a few special cases. Empirical reasoning coupled with results from model experiments may lead to use of the technique in a wide range of problems occurring in mining geophysics. Research in this direction is required and probably is justified, since unique identification of anomaly-causing bodies by means of surface geophysical measurements may result.

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GEOPHYSICS, VOL XXIV, NO. 3 (JULY, 1959), PP. 547–565, 12 FIGS.

MATHEMATICAL FORMULATION AND TYPE CURVES FOR INDUCED POLARIZATION*

HAROLD O. SEIGEL†

ABSTRACT

A basic mathematical formulation is developed for overvoltage and other induced polarization phenomena. Starting from the fundamental representation of a volume dipolar distribution, one is led to the concept of a change in apparent conductivity due to polarization effects. The mathematical solution of induced polarization phenomena, therefore, reduces to the appropriate solution of Laplace's equation for the same geometry and conductivity distribution ignoring polarization, followed by partial differentiation of the apparent resistivity function so determined. The dielectric constants of the media are not involved in the solution.

As examples of the use of the representation, the response of a polarizable sphere and of a polarizable lower layer in a typical two-layer case are presented. Actual field results are shown illustrating the use of the latter solution.

INTRODUCTION

The early workers in the field of induced polarization, such as Schlumberger (1930) and Dakhnov (1941) have given no published indication of any attempt at mathematical representation of the phenomena they were investigating. Bleil (1953), who has been the first in North America to publish on overvoltage or any other induced polarization phenomenon, also presented no mathematical formulation.

The writer's first attempt at a representation for a volume polarization distribution was presented in a thesis for the National Research Council of Canada (1948) and was expanded in his Ph.D. thesis on overvoltage (1949). In the latter thesis the experimental proof of the successful application to the detection of sulphide mineralization *in situ* was presented.

The field procedure involved the application of a constant potential between two points of a medium under investigation for a few seconds; the abrupt interruption of the applied voltage and the measurement of transient voltages existing in the medium from a few milliseconds after the interception.

A second phenomenon (or group of phenomena), termed the "normal" or background effect, was recognized in the course of the field investigations as being present in all rocks, consolidated or otherwise, even when totally lacking in metallic sulphide minerals. It was found that the "normal" effect generally lay within relatively narrow limits for most rocks and could, therefore, be resolved from overvoltage effects. In the thesis (p. 63–71) it was suggested that the "normal" effect in consolidated rocks might be due to a number of phenomena of which certain electrokinetic effects (electro-osmosis plus "streaming potential") might predominate. The more recent investigations of Vacquier (1957) add

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electrodialysis of clay across semi-permeable partitions formed by sand grains in unconsolidated sediments.

The need of a mathematical model of the overvoltage and "normal" effect became great when it was apparent that the overvoltage phenomenon could be employed in exploration for sulphide mineralization. The model could be used in the interpretation of field data in terms of dimensions and physical properties of the various geological factors involved.

In the Ph.D. thesis it was shown that the overvoltage effect associated with a single metallic conducting sphere in an electrolyte is the same as that due to a dipolar source whose moment is proportional and antiparallel to the average current density vector in the vicinity. A small volume containing a number of such particles would then be expected to act at an external point as a dipolar source whose moment is the combined effect (including interaction) of the particles. In the thesis treatment it was assumed that a dipolar source acted at a distance in accordance with electrostatic laws rather than electrodynamic laws. Simple, idealized geologic examples were then solved mathematically, e.g., a uniform mineral dissemination through a homogeneous semi-infinite earth. An extension of this case to the homogeneous infinite earth, i.e., wherein all electrodes are buried in the earth at a depth much greater than their separation, reveals that the polarization potentials for the same current flow remain unchanged, but the primary voltage drops to half its value. In other words, the ratio of the secondary (transient) voltage to primary voltage (steady state) should be dependent on the position of the electrodes relative to the boundaries of a mass of homogeneous polarizable material.

Using a large box containing a homogeneous mixture of crushed pyrite of a certain particle size range, crushed rock and saline electrolyte, this deduction was tested and found to be incorrect. It was quickly found that the ratio of secondary (transient) voltage over primary voltage depends only on the material, not on its shape, nor on the configuration of electrodes used or their location within the mass. This took place in January, 1950. About the same time it became apparent that the "normal" ratio displayed the same disregard for electrode configuration or surface topography, even when the latter was extremely dissected, as at Jerome, Arizona, and was approximately the same for electrodes on surface or in mine workings far underground.

It became apparent that a different mathematical model was required to predict the dependence of the observed transient voltages on the physical properties of the materials involved. This formulation, which is reproduced in detail below, has been tested experimentally in the laboratory and on field examples and leads to agreement with the results obtained. Starting with the fundamental approach of a volume distribution of dipolar sources, it leads directly to the concept of change of apparent resistivity with time, due to either normal induced effects or to the effect of a dissemination of sulphide particles.

Of the mathematical representations which have been published since this

development was made, it is interesting to note that the mathematical formulation of Frische and von Buttlar (1957) employs the electrostatic model in conjunction with induced polarization in unconsolidated sediments. A recent representation, by Henkel (1958), leads to the same end product as the writer's present formulation, but it is less fundamental in approach, since it ignores the basic concept of a volume dipolar distribution.

MATHEMATICAL FORMULATION OF THE DYNAMIC DIPOLAR REPRESENTATION

All dipolar charge effects will be included in the following discussion, whether due to dielectric absorption, electrodialysis, overvoltage, or other sources . The experimental conditions assumed are that a step function of voltage is instantaneously applied to two electrodes immersed in a medium, and, after a selected interval, it is interrupted instantaneously. The voltage existing between two nonpolarizing electrodes in the medium is observed after the interruption. These residual voltages may be due to any combination of the various phenomena mentioned above.

The earlier representation of the dipolar distribution set up by an electric field in an ionic conductor was a static one, i.e., we considered only the electrostatic field of such dipoles as causing the observed voltage gradients after the interruption of the primary field. Such a representation ignores the effect of conductivity changes in the medium on the field of the secondary dipoles in favor of the effect of changes in the dielectric constant, and hence is not valid for slowly varying fields.

We now propose to introduce a dynamic representation or model for polarization effects.

The secondary response due to these phenomena is represented as that due to a volume density of dipolar sources, the current from which must obey the normal steady current flow boundary conditions at discontinuities in conductivity.

Our postulate is: The action of the primary field is to create a volume distribution of current dipoles antiparallel to the field at each point in the medium, and with volume current moment strength $\vec{M} = -m\vec{j}$, where $\vec{j}$ is the primary current density. The factor m is assumed to be a constant, called the "chargeability." It is a property of the medium and includes all polarization effects, but it depends on the duration interval of the applied voltage.

The potential at a point, P, at a distance r from the volume dipole element of current strength $\vec{M}dv$ in a medium of conductivity σ is

$$d\Phi = \frac{1}{4\pi\sigma} \vec{M} \cdot \nabla \left(\frac{1}{r} \right) dv$$

when the gradient is taken at the dipole (see Figure 1).

The total potential at the field point, P, due to a volume distribution of such dipoles, is then

$$\Phi = \frac{1}{4\pi}\iiint \frac{\vec{M}}{\sigma}\cdot\nabla\left(\frac{1}{r}\right)dv.$$

However, by use of the identity

$$\operatorname{div}\left(\frac{\vec{M}}{\sigma r}\right) = \frac{1}{r}\operatorname{div}\left(\frac{\vec{M}}{\sigma}\right) + \frac{\vec{M}}{\sigma}\cdot\nabla\left(\frac{1}{r}\right),$$

we obtain

$$\Phi = \frac{1}{4\pi}\iiint\left[\operatorname{div}\left(\frac{\vec{M}}{\sigma r}\right) - \frac{1}{r}\operatorname{div}\left(\frac{\vec{M}}{\sigma}\right)\right]dv.$$

By Gauss' theorem we may write this as

$$\Phi = \frac{1}{4\pi}\iint_S \frac{M_n}{\sigma\cdot r}\,dS - \frac{1}{4\pi}\iiint_V \frac{1}{r}\operatorname{div}\left(\frac{\vec{M}}{\sigma}\right)dv$$

where S is the surface bounding the volume V.

Thus, the volume distribution of current dipoles is mathematically equivalent to a volume distribution of current sources of density equal to $-\operatorname{div}\vec{M}$ (σ constant within V, understood) and a surface distribution of strength M_n (normal component of $\vec{M}$ out of the surface S).

Now if $\vec{j}$ is the current density vector at any point in the medium, and i is the volume density of free current sources (i.e., due to primary current electrodes) then by the law of conservation of charge:

$$\operatorname{div}\vec{j} = i.$$

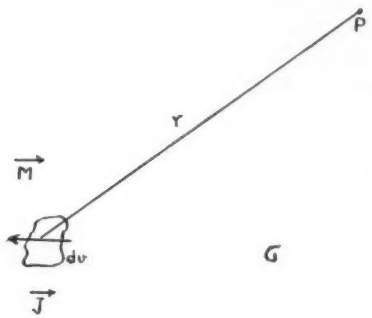

FIG. 1. Volume dipolar element.

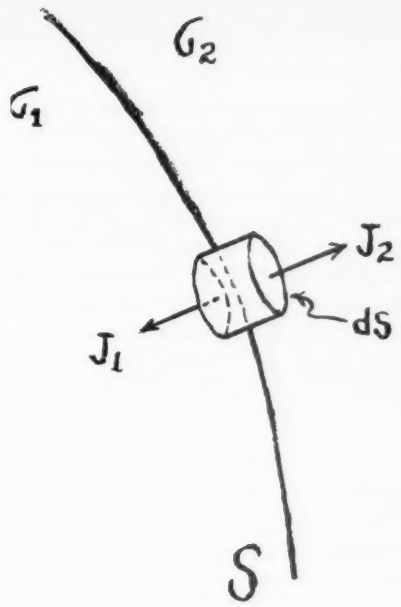

FIG. 2. Boundary conditions.

To these free sources i we must now add the effective source density $-\text{div } \vec{M}$,

$$\text{i.e., } \text{div } \vec{j} = i - \text{div } \vec{M},$$

$$\text{or, } \text{div } (\vec{j} + \vec{M}) = \vec{i}. \tag{1}$$

At a discontinuity in M, σ, or both, we may determine our boundary conditions by considering the normal current flow out of the faces of a small disc with sides normal to the interface and faces dS parallel to it (see Figure 2).

Equating current outflow to current inflow within the disc, we find, in the absence of free sources on the interface, that

$$-j_1 + j_2 = M_1 - M_2,$$

$$\text{or, } (j + M)_1 = (j + M)_2 \tag{2}$$

Thus, the vector $\vec{j}+\vec{M}$ or $\vec{j}(1-m)$ is everywhere solenoidal, except in the presence of free sources or sinks, and its normal component is continuous across discontinuities in σ and m.

If the impressed electric field due to externally supplied sources is $\vec{E}$, then

the original impressed current density vector is $\vec{j}=\sigma\vec{E}$. The vector $\vec{j}(1-m)$ in the presence of the dipolar distribution plays the role of $\vec{j}$ in the absence of such dipoles. Thus the total current density in the presence of the dipoles is $\sigma(1-m)\vec{E}$. The net effect is to reduce σ by the factor $(1-m)$.

Thus, whenever we can obtain the current flow steady state solution for any problem involving conductors whose conductivities σ_i are known, we have also obtained the solution for the same potential problem taking into account the secondary dipolar distributions. The one step required is to change σ_i to $\sigma_i(1-mi)$ in each instance. The difference between the two potential functions will then give us the peak secondary voltages to be experienced from polarization effects.

The question of form of decay curve is another matter entirely and depends on determination of the relative amounts contributed to the peak secondary by the dipoles in the various media involved, assuming the decay form for each medium is known.

SPECIAL CASES

(1) *Homogeneous Medium*

If we have a mass of homogeneous material of any size and shape and induce current I into it at two or more points (sources and sinks), then the primary potential drop between any two electrodes (serving as potential electrodes) will be, in the absence of volume polarization effects,

$$\Phi = \frac{I}{\sigma} F$$

where σ is the uniform conductivity of the medium, F is a function of the shape of the body and positions of all electrodes in it.

In the presence of the dipoles, the primary potential drop is altered to

$$\Phi' = \frac{I}{\sigma(1-m)} F$$

where m is the uniform chargeability of the medium. The peak secondary voltage is

$$\Phi' - \Phi = \left(\frac{IF}{\sigma}\right)\left(\frac{m}{1-m}\right)$$

and the ratio of the peak secondary to the primary voltage is

$$(\Phi' - \Phi)/\Phi' = m. \tag{3}$$

Thus, in any homogeneous isotropic medium, for an arbitrary electrode configuration, the ratio of peak secondary to primary voltage is equal to the charge-

ability m of the medium, provided that by the "primary" voltage we mean the voltage between the potential electrodes at the instant of the interruption of the primary field.

The importance of this is manifold. Firstly, in uniform isotropic media, all electrode configurations will yield the same ratio of peak secondary to primary voltages. Secondly, the ratio will be independent of shape of surface or boundaries, i.e., topography will not affect the ratio. This has been one of the puzzling, but welcome, observations in areas of great ruggedness, e.g., Arizona, Peru, and British Columbia. The ratios are expected to be unaltered in the transition from surface to underground operations. Thirdly, the calculation of polarization characteristics of rock samples from measurements in the laboratory is greatly simplified. Assuming that there will be negligible interaction between electrodes due to overvoltage at the current electrodes, the ratios of primary and secondary voltages will, for homogeneous isotropic samples, be independent of the electrode positions, and specimen size and shape.

(2) *Heterogeneous Media*

If the medium under consideration is composed of n different materials of conductivities σ_i, $i=1 \cdots n$, then the primary voltage in the absence of dipolar action is generally expressible as $\Phi=\Phi(\sigma_i)$ for fixed dimensions and electrode positions.

In the presence of the dipoles $\Phi'=\Phi(\sigma_i')$ where $\sigma_i'=\sigma_i(1-m_i)$ and where m_i ($i=1, 2, \cdots, n$) are the chargeabilities of the various media

Now

$$\Phi' = \Phi(\sigma_i') = \Phi(\sigma_i) + \sum_i (\sigma_i' - \sigma_i)\Phi_i,$$

where $\Phi_i=\partial\Phi/\partial\sigma_i$. After differentiation σ_i is replaced by $\sigma_i(1-\theta_i m_i)$, where $0\leq\theta_i\leq 1$. But $\sigma_i'-\sigma_i=-\sigma_i m_i$. Therefore,

$$\Phi' = \Phi - \sum_i \sigma_i m_i \Phi_i. \tag{4}$$

Thus, whenever an increase of conductivity of one of the components of the system will result in a decrease of primary voltage (which is true except in certain special configurations) the effect of the presence of the dipoles is to increase the primary voltage.

The apparent chargeability of the medium is given by

$$m_a = (\Phi' - \Phi)/\Phi' = \frac{-1}{\Phi'} \sum_i \sigma_i m_i \Phi_i = + \sum_i m_i \rho_i \partial\Phi/\partial\rho_i, \tag{5}$$

where $\rho_i=1/\sigma_i$ is the resistivity of the ith medium.

Generally, a function ρ_a is defined which is merely a constant geometric factor times the primary voltage.

Then

$$m_a = \sum_i m_i \rho_i \frac{\partial \rho_a}{\partial \rho_i} \Big/ \rho_a' \tag{6}$$

(accent indicating inclusive of dipolar action)

$$\frac{\partial \rho_a}{\partial \rho_i}$$

is taken at

$$\rho_i / 1 - \theta_i m_i.$$

For the most types of polarization $m \ll 1$ and is often of the order of 10^{-2}. Then $\theta_i m_i \ll 1$, and $\rho_a' \approx \rho_a$.

Therefore, we may write

$$m_a \approx \sum_i m_i \partial \log \rho_a / \partial \log \rho_i \tag{6'}$$

Now ρ_a is homogeneous of the first order in the ρ_i, i.e.,

$$\rho_a(t\rho_i) = t\rho_a(\rho_i)$$

This follows from the expression for the primary voltage between two points, P_1 and P_2, as $V = \int_{P_1}^{P_2} E_s dS$, i.e., as the line integral of the tangential component of the field over an arbitrary path joining the points. We may write $E_s = j_s \rho$, where j_s is the tangential component of the current vector, and ρ is the resistivity at the point of integration.

If all resistivities are multiplied by the factor t, then the primary voltage and hence apparent resistivity is altered proportionally as well, since the current distribution for constant total current will remain unaltered.

For homogeneous functions of the first order, the following theorem holds:

$$\rho_a = \sum_i \rho_i \partial \rho_a / \partial \rho_i. \tag{7}$$

This may be formally derived simply from the Taylor expansion

$$\rho_a(0) = \rho_a(t\rho_i) - t\left(\sum_i \rho_i \partial \rho_a(t\rho_i) / \partial \rho_i \right) + \frac{t^2}{2!}\left(\sum_i \rho_i \partial^2 \rho_a(t\rho_i) / \partial \rho_i^2 \right) \cdots .$$

Since $\rho_a(0) = 0$ and $\rho_a(t\rho_i) = t\rho_a(\rho_i)$ we obtain, after equating to zero the coefficient of t in the identity on the right side

$$\rho_a = \sum_i \rho_i \partial \rho_a / \partial \rho_i.$$

This may be otherwise expressed as

$$\sum_i \partial \log \rho_a / \partial \log \rho_i = 1. \tag{8}$$

Thus we may write

$$m_a = \left[\sum_i m_i \, \partial \log \rho_a / \partial \log \rho_i \right] \Big/ \sum_i \partial \log \rho_a / \partial \log \rho_i. \tag{9}$$

In general $\partial \log \rho_a / \partial \log \rho_i$ is positive, and m_a will lie intermediate to the extreme m_i. If all m_i are equal, say to m_0, then regardless of the resistivity distribution $m_a = m_0$ also.

m_a can lie externally to the extreme m_i only when $\partial \log \rho_a / \partial \log \rho_i$ is negative for some i. Actual examples might be a thin bed lying entirely between a current and potential electrode; or measurements down a drill hole wherein there is a marked resistivity contrast between the drill fluid and the wall rock. An increase in resistivity of the thin bed or of the drill hole fluid may cause a decrease in apparent resistivity. Other possibilities may present themselves.

When we are dealing with only two media, formula 6′ becomes

$$m_a = m_1 \frac{\partial \log \rho_a}{\partial \log \rho_1} + m_2 \frac{\partial \log \rho_a}{\partial \log \rho_2} = m_1 + (m_2 - m_1) \frac{\partial \log \rho_a}{\partial \log \rho_2}$$

or

$$\frac{m_a - m_1}{m_2 - m_1} = \frac{\partial \log \rho_a}{\partial \log \rho_2} \tag{6″}$$

This is a useful formula in dealing with two media, of which only the second is abnormally polarizable.

The mathematical representation above applies to peak polarization voltages, and formulas 6, 6′, 9, etc., apply to the resultant secondary voltage observed immediately after the interruption of the primary field. Assuming little dipolar interaction, however, the above formulas apply to any phase of the voltage decay curve and to any type of measurement, e.g., integration over a specified time interval.

To the approximation that $m_i \ll 1$, for all i the procedure for determining the net polarization response of a heterogeneous medium reduces to the following two steps.

1. Obtain the mathematical or experimental (model) apparent resistivity solution of the problem as a function of the individual media resistivity values using the electrodal configuration desired.

2. Differentiate the logarithm of the apparent resistivity curve, mathematically or graphically, with respect to the resistivity of each component.

The polarization factor, or "chargeability" m_i of the ith medium is then weighted in proportion to (2).

This is a direct procedure and remarkably simple in relation to the dictates of the older dielectric representation which involved elaborate integration of volume dipolar effects.

Significance of Conductivity Contrast

As formula 6″ indicates, the polarization effect of an anomalous body is related both to its polarization contrast and to the effect which a change in its resistivity would have on the overall apparent resistivity picture.

In a variety of examples where precise mathematical solutions are possible, it is found that when the ratio of ρ_2/ρ_1 becomes either very large or very small, a small percentage change in ρ_2 will no longer affect the voltage distribution (and apparent resistivity) in the outside medium. This might be termed a "saturation" phenomenon. In either saturation region, therefore, the weighting factor

$$\frac{\partial \log \rho_a}{\partial \log \rho_2}$$

will be very small and likewise the polarization effect for given m_2 and m_1.

As a practical consequence, the overvoltage response of a concentrated sulphide body of relatively high conductivity would be less than one might have expected from its percentage of sulphide mineralization. For this reason and because interconnected sulphide particles give overvoltage effects only at their points of current entry and exit—the overvoltage method is rather weak in the realm of concentrated sulphides (25 percent or greater). Its best field of application is in the realm of investigation of truly disseminated sulphide bodies, as, for example, most "porphyry" copper-type deposits.

As an example of the saturation effect, one may refer to Figure 8 of Bleil's paper (1953), which shows that the overvoltage effect of the Gossan Lead (pyrrhotite) body decreases as the more massive portion of the body, is approached.

Electrodal Arrays

An electrode array for resistivity or induced polarization surveys generally consists of four earthed contacts, two for current passage and two for voltage measurements. Three different arrays that have been employed are as follows

1. *Wenner or Four-Electrode Array.* This is the classic array consisting of four collinear, equally-spaced electrodes with common separation designated a. When surveying with this type of array, all four electrodes are moved in unison along a line. The spacing a is selected on the basis of the desired depth of penetration, i.e., probable depth to the target desired. Measurements are plotted against the mid-point of the spread.

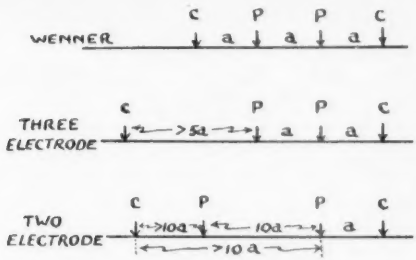

FIG. 3. Typical electrodal arrays.

2. *Three-Electrode Array.* When one of the current electrodes from the Wenner array is moved to a point a great distance, such as 5a, from all the other electrodes, its contribution to the voltage picture will become so small (usually) that it may be ignored in calculations. Now only the remaining three equi-spaced electrodes need be moved in unison during a survey. Measurements are plotted against the mid-point of the current and first potential electrode.
3. *Two-Electrode Array.* When one of the current electrodes and its adjacent potential electrode of the Wenner array are moved to locations a large distance, such as 10a, from each other and from the two remaining electrodes we are left with the two-electrode array. Only the two remaining electrodes need now be moved along lines to carry out a survey. The far electrode need not be collinear with the near electrode. Measurements are plotted against the position of the mid-point of the current and near potential electrode (see Figure 3).

Each of these various electrode arrays has its own advantages and disadvantages. For example, it is not surprising that the removal of one or more electrodes out of the field of influence of the other increases the effective depth of penetration of the array. This is illustrated in the Example 1, the Response of a Sphere, which follows below.

Example 1. The Response of a Sphere. The effect of a sphere on the voltage distribution due to current flow from a point current source may, to a good approximation, be represented by the effect of the same sphere in a uniform field equal in magnitude and direction to that of the point source at its center (Stratton, 1941).

Consider a sphere of volume V, resistivity ρ_2, chargeability m_2, in a medium of resistivity ρ_1, chargeability m_1 in the presence of a uniform electric field of strength E, inclined at an angle θ to the axis of a spherical co-ordinate system (r, θ, ϕ) with the origin of the system at the center of the sphere (see Figure 4). The modification to the potential distribution in the external medium due to the presence of the sphere may be expressed as (Stratton, 1941)

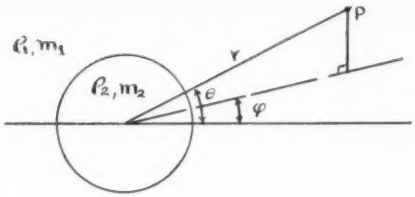

FIG. 4. Co-ordinate system for response of a sphere.

$$\Delta\Phi = E\frac{3V}{2\pi}\frac{\cos\theta}{r^2}\left(\frac{\rho_2 - \rho_1}{\rho_1 + 2\rho_2}\right). \tag{10}$$

The value of E, for a current electrode C on the surface of the earth is $I/2\pi R^2$, where I is the current and R the distance from the electrode to the center of the sphere (see Figure 5).

The voltages and apparent resistivities measured in the presence of the sphere will consist of two parts, the first due only to the external medium and the second to the disturbing effect of the sphere of anomalous material. Both will be functions of the array selected and the geometry of the situation.

On the assumption that the primary effect on the apparent resistivity is small, we can, to the first approximation, separate the geometric factor from the physical property factor. It can be shown that we may write

$$\frac{m_a - m_1}{m_2 - m_1} = F\frac{9V}{2\pi d^3}\rho_1\rho_2/(\rho_1 + 2\rho_2)^2. \tag{11}$$

Where F is a form factor depending on the array employed, the electrode spacing relative to the depth "d" of the center of the sphere below the array, and the lateral displacement of the line of traverse relative to the vertical axis through

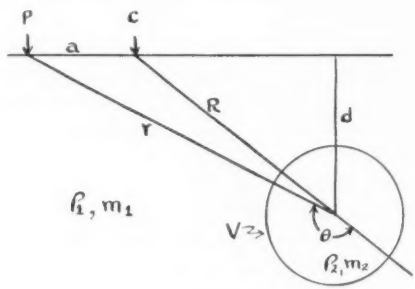

FIG. 5. The buried sphere parameters.

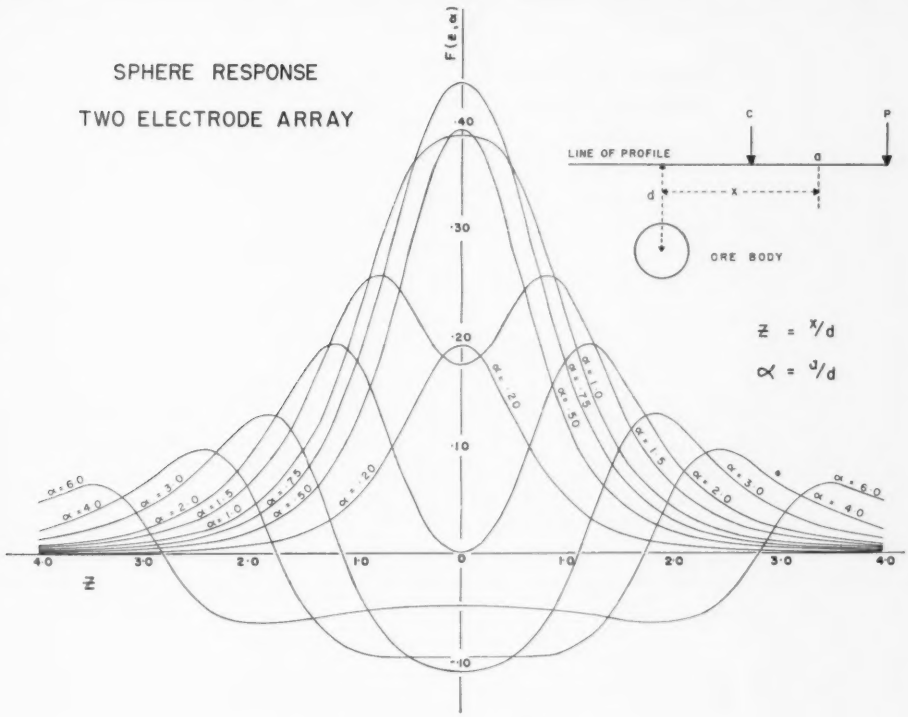

FIG. 6. Sphere response: two-electrode arrays.

the center of the sphere. Incidentally, the same form factor applies for the shape of the corresponding resistivity anomaly curve. That portion of the right hand side of (11), which entails only the resistivities, is of interest. It is actually dimensionless and depends only on the ratio of ρ_2/ρ_1. For very large or very small values of this ratio, this resistivity factor approaches zero. This is the "saturation effect" referred to earlier. The factor is a maximum when $\rho_2/\rho_1 = 0.5$, i.e., when the sphere is just twice as conductive as its surroundings. This illustrates the optimum efficiency of the overvoltage method on detection of moderate disseminations of sulphide mineralization.

The form factor F has been plotted in Figure 6 for the two-electrode array and in Figure 7 for the three-electrode array. The following points are worthy of note:

1. The curve form depends on the electrode array and the value of α, the ratio of the spacing to the minimum distance to the center of the sphere.

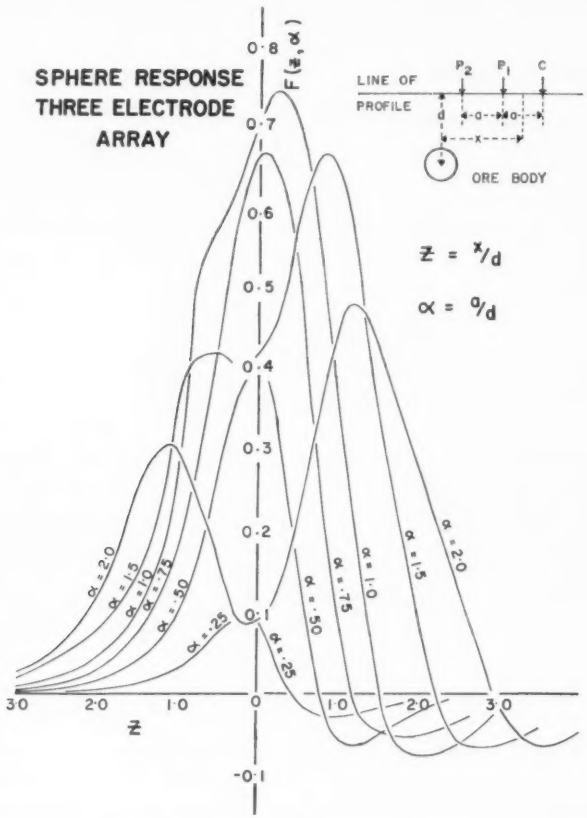

FIG. 7. Sphere response: three-electrode arrays.

2. For each array the response increases with α until a certain value is obtained, then decreases. The optimum value of α has been found to be
   0.70 for the two-electrode,
   1.1 for the three-electrode,
   1.2 for the Wenner array.

There is thus some meaning to the term "depth of penetration" and it may be said that for a given electrode separation, the two-electrode, three-electrode, and Wenner arrays stand in order of decreasing depth penetration.

3. The maximum anomalous indication for any spacing on the various arrays stands in the ratio 2/1. 2/1 with the three-electrode array leading and the Wenner lagging all.

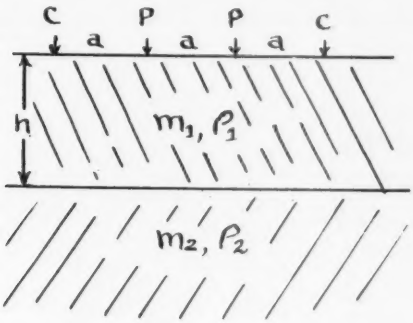

FIG. 8. The two-layer parameters.

The above are some of the factors which may influence the selection of the array to use for a particular problem.

Example 2. The Two-Layer Case, Wenner Array. The mathematical resistivity solution of the two-layer case has been variously presented (e.g., Roman, 1934).

It is assumed that the upper medium is characterized by resistivity ρ_1 and chargeability m_1 and the lower medium by parameters ρ_2 and m_2. The electrode spacing is a and the thickness of the upper layer is h, both in arbitrary units. The array employed is the Wenner (see Figure 8).

As the solution of the resistivity problem we may write as apparent resistivity

$$\rho_a = \rho_1\left(1 + 4\sum_{n=1}^{\infty}\frac{k^n}{(1+4n^2/\alpha^2)^{1/2}} - 2\sum_{n=1}^{\infty}\frac{k^n}{(1+n^2/\alpha^2)^{1/2}}\right), \tag{12}$$

where

$$k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}, \quad \text{and} \quad \alpha = a/h.$$

A plot of ρ_a/ρ_1 versus α may be seen, for example, in the publication of Mooney and Wetzel (1956).

$$\frac{\partial \log \rho_a}{\partial \log \rho_2} = \frac{m_a - m_1}{m_2 - m_1}$$

$$= \frac{\rho_1}{\rho_a}(1-k^2)\left[2\sum_{n=1}^{\infty}\frac{nk^{n-1}}{(1+4n^2/\alpha^2)^{1/2}} - 2\sum_{n=1}^{\infty}\frac{nk^{n-1}}{(1+n^2/\alpha^2)^{1/2}}\right] \tag{13}$$

The function on the right, called for simplicity $B(k, \alpha)$ is plotted on the accompanying charts, on a log-log basis as a function of α for negative values of k in Figure 9 (i.e., $\rho_2 < \rho_1$) and for positive values of k in Figure 10.

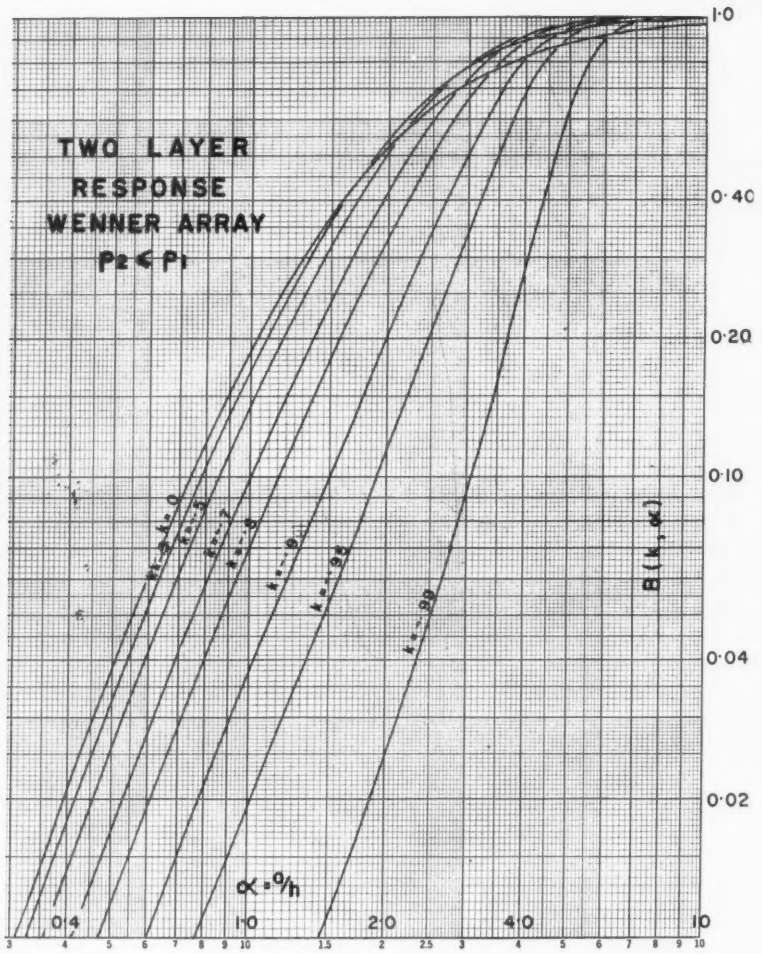

FIG. 9. Two-layer response, k negative.

To illustrate the application of these curves to actual field examples, two pairs of field curves are presented. The first (Figure 11) was obtained in Custer County, Colorado, where disseminated pyritic mineralization is widespread in an acid intrusive stock, but where there has been complete oxidation of sulphides down to the present water table (about 20′–30′). On the log-log chart are shown the

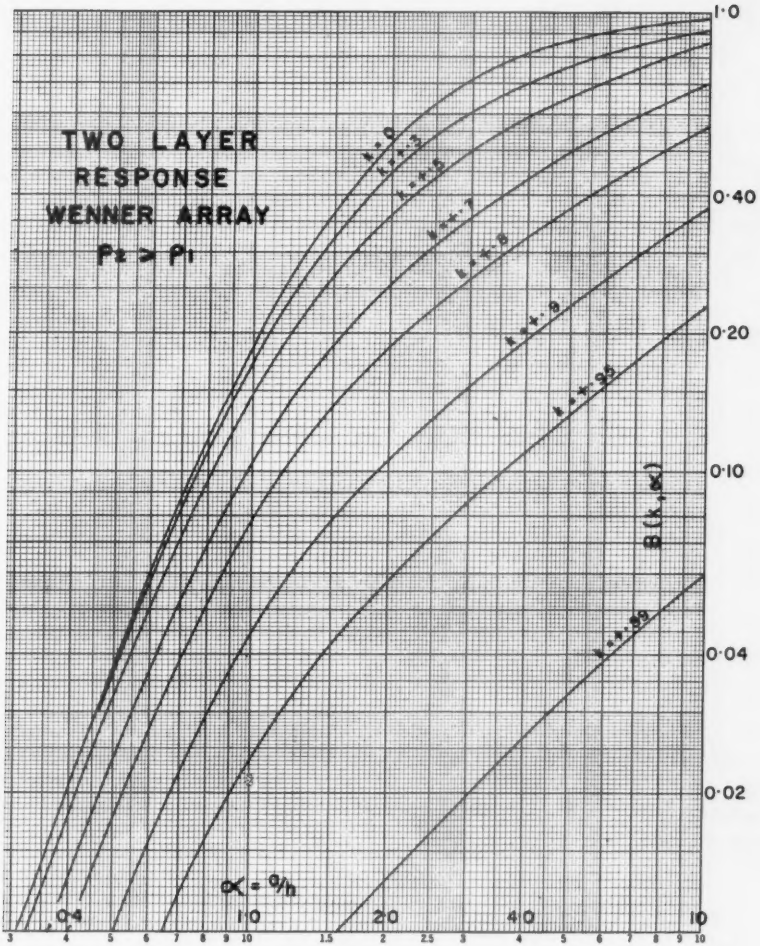

FIG. 10. Two-layer response, k positive.

theoretical curves which fit the experimental resistivity and chargeability curves. The experimental data are well fitted by the following parameters:

$\rho_1 = 135$ ohm meters, $\rho_2 = 30$ ohm meters $(k = -0.6)$;

$h = 24$ ft, $m_1 = 10$, $m_2 = 72.0 \times 10^{-3}$ seconds.

The second example (Figure 12) is from Cuajone, Peru, where disseminated

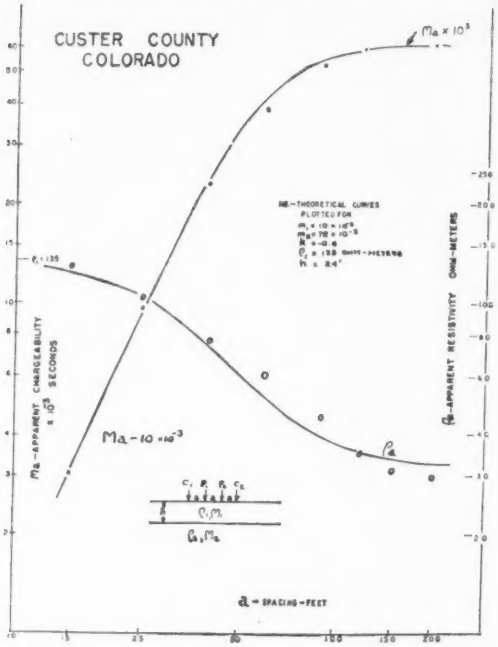

FIG. 11. Field example: Custer County, Colorado.

pyrite-chalcopyrite mineralization in an intrusive porphyry is overlain by an unmineralized later volcanic flow of considerable thickness. Once again the experimental resistivity and chargeability curves are closely fitted by theoretical curves, with the following parameters

$\rho_1 = 50$ ohm meters, $\rho_2 = 200$ ohm meters,
$k = 0.6$, $h = 100$ meters, $m_1 = 7$, $m_2 = 46.0 \times 10^{-3}$ seconds.

In both these examples the quantity m_a measured is the time integral over one second of the transient voltage resulting from the interruption of a three-second duration square wave, divided by the steady state voltage observed during the three seconds of the current passage. It has the units of milliseconds.

ACKNOWLEDGMENTS

The writer is indebted to Newmont Exploration Limited, on whose behalf the theoretical development was undertaken, for permission to publish this paper.

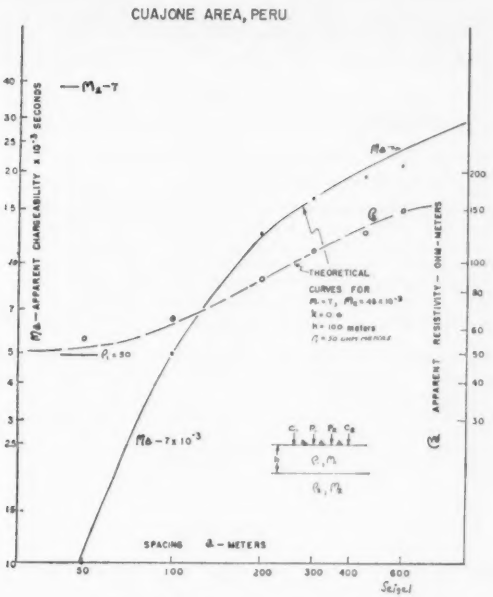

FIG. 12. Field example: Cuajone, Peru.

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GEOPHYSICS, VOL. XXIV, NO. 3 (JULY, 1959), PP. 566–579, 4 FIGS.

POTENTIAL DISTRIBUTION DUE TO A CYLINDRICAL ELECTRODE MOUNTED ON AN INSULATING PROBE*

LEENDERT DE WITTE† AND ROY W. GOULD‡

ABSTRACT

The potentials around a finite cylindrical electrode can be obtained by dividing the electrodes into rings of equal thickness and substituting an infinitely thin current ring for each of the slices. The field of an infinitely thin ring electrode mounted on an insulating cylindrical probe of the same diameter can be found by combining the properties of the delta function with a solution of Laplace's equation in cylindrical co-ordinates. Combination of solutions for the infinitely thin rings under the condition that the potential of the electrode surface be constant leads to a system of simultaneous linear equations. By increasing the number of slices, the potential around the finite electrode can be found arbitrarily close.

The problem of a cylindrical electrode on a sonde located coaxially in a conducting hole, drilled through a medium of different conductivity, is treated by the same method. This arrangement is of interest in electrical logging of drill holes.

Numerical examples have been calculated on an IBM 650 magnetic drum computer. The potential along the surface of the insulating probe, at distances larger than twice the electrode length, can be approximated with good accuracy by assuming that all of the current is emitted from an infinitely thin ring located in the median plane of the electrode.

INTRODUCTION

The problem treated in this paper arises typically in electrical surveying of drill holes where cylindrical electrodes mounted on an insulating cylindrical sonde of approximately the same diameter are employed. It is, however, not unlikely that the analysis presented here will be applicable to many other problems in electrical engineering and electrical analog systems.

The potential distribution around a right charged circular cylinder was treated by Smythe (1956) for cylindrical electrodes with conducting end faces in a homogeneous medium. For cylindrical electrodes of a length large compared to the diameter, a prolate spheroid approximation is frequently used (Smythe, 1950, p. 165–167; Owen and Greer, 1951). Limitations of the prolate spheroid method in the well surveying problem and an alternate solution to the problem of long cylindrical electrodes were described in a recent publication by de Witte, Fournier, and Tejada-Flores (1957).

The present solution is best suited for problems where the length of the electrode does not exceed ten times the electrode diameter. An advantage of the present method is that the effects of other cylindrical boundaries which are coaxial with the electrode surface are easily taken into account. The solution proceeds by first finding the field due to an infinitely thin ring mounted on a cylindrical probe of the same diameter and then to present a finite cylindrical electrode by a succession of rings whose thickness can be made arbitrarily small.

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POTENTIAL DISTRIBUTION AROUND AN INFINITELY THIN CONDUCTING RING MOUNTED ON A CYLINDRICAL INSULATING SONDE

Let us assume an infinite insulating cylinder of radius a, coaxial with the z-axis of a cylindrical co-ordinate system. In the horizontal plane through the origin an infinitely thin conducting ring also of radius a is mounted on the insulating cylinder. The cylinder is surrounded by a medium of resistivity, R, and a total current, ϑ, flows from the ring into the surrounding medium (Figure 1).

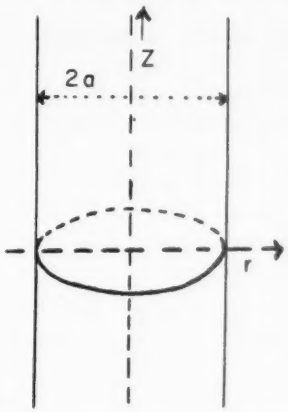

FIG. 1. Schematic of a thin conducting ring on an insulating cylindrical sonde.

The potential distribution will obey Laplace's equation: $\nabla^2 V = 0$. The general solution for the potential in terms of the cylindrical co-ordinates will be (Smythe, 1950, p. 194; Frankel, de Witte , and Porter, 1952):

$$V = \int_0^\infty [A(\lambda) I_0(\lambda r) + B(\lambda) K_0(\lambda r)] \cos \lambda z d\lambda. \tag{1}$$

Since $I_0 \to \infty$ for $r \to \infty$, and since V must be zero at infinity, the coefficient $A(\lambda)$ must equal zero, so that we have

$$V = \int_0^\infty B(\lambda) K_0(\lambda r) \cos \lambda z d\lambda. \tag{2}$$

At the surface of the sonde the radial current density

$$-\frac{1}{R}\left(\frac{\partial V}{\partial r}\right)$$

will everywhere be zero except for $z = 0$ where the radial current density will be infinite (since a finite current ϑ is leaving from an infinitely small area).

The total current $\mathcal{I}$ leaving the sonde will be given by

$$\mathcal{I} = -\int_{-\infty}^{\infty} \frac{1}{R}\left\{\left(\frac{\partial V}{\partial r}\right)_{r=a}\right\} 2\pi a dz. \tag{3}$$

We now make use of the function $\delta(z)$ as defined by:

$$\delta(z) = \lim_{\alpha \to 0}\left(\frac{1}{\pi}\,\frac{\alpha}{z^2+\alpha^2}\right). \tag{4}$$

This function is known as Dirac's delta function. It is the derivative of Heaviside's unit step function. Its value is zero everywhere except at the origin where it is infinite. Its integral (the unit step function) or the area under the curve of the δ function is unity, so that we can write

$$\int_{-\infty}^{\infty} \delta(z)dz = 1. \tag{5}$$

Relation (5) can be obtained directly by integrating (4).

Combining (3) and (5), we have

$$\int_{-\infty}^{\infty} \mathcal{I}\delta(z)dz = -\int_{-\infty}^{\infty} \frac{2\pi a}{R}\left(\frac{\partial Vz}{\partial r}\right)_{r=a} dz,$$

so that

$$\mathcal{I}\delta(z) = -\frac{2\pi a}{R}\left(\frac{\partial V}{\partial r}\right)_{r=a}. \tag{6}$$

We can use this relation to solve for $B(\lambda)$ in equation (2)

$$\left(\frac{\partial V}{\partial r}\right)_{r=a} = \int_0^{\infty} - B(\lambda)\lambda K_1(\lambda a)\cos \lambda z d\lambda,$$

since

$$\frac{dK_0(r)}{dr} = -K_1(r).$$

Substitution into (6) gives

$$\mathcal{I}\delta(z) = \frac{2\pi a}{R}\int_0^{\infty} B(\lambda)\lambda K_1(\lambda a)\cos \lambda z d\lambda. \tag{7}$$

In order to simplify this relation, we make use of the Fourier transform of $\lambda(z)$. By the Fourier integral theorem:

$$\delta(z) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \delta(\lambda)e^{\pm i\lambda z}d\lambda,$$

where $\delta(\lambda)$ is the Fourier transform of $\delta(z)$ and is given by:

$$\delta(\lambda) = \int_{-\infty}^{\infty} \delta(z) e^{-i\lambda z} dz.$$

Substituting relation (4) gives

$$\delta(\lambda) = \lim_{\alpha \to 0} \left[\frac{\alpha}{\pi} \int_{-\infty}^{\infty} \frac{e^{-i\lambda z}}{z^2 + \alpha^2} \right] dz,$$

according to the relation (Bierens de Haan, 1867, p. 149):

$$\int_{-\infty}^{\infty} \frac{e^{-pxi} dx}{q^2 + x^2} = \frac{\pi}{q} e^{-|p|q}.$$

$$\delta(\lambda) = \lim_{\alpha \to 0} \left[e^{-|\lambda|\alpha} \right]. \tag{8}$$

Using (8) in the Fourier integral expression for $\delta(z)$, we have

$$\delta(z) = \lim_{\alpha \to 0} \left[\frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-|\lambda|\alpha} e^{+i\lambda z} d\lambda \right],$$

$$= \lim_{\alpha \to 0} \left[\frac{1}{\pi} \int_{0}^{\infty} e^{-|\lambda|\alpha} \cos \lambda z d\lambda \right]. \tag{9}$$

Since

$$\lim_{\alpha \to 0} e^{-|\lambda|\alpha} = 1,$$

we can multiply the right-hand side of (7) by this quantity and then substitute relation (9) for $\delta(z)$ in the left-hand side:

$$\lim_{\alpha \to 0} \left[\frac{1}{\pi} \int_{0}^{\infty} \vartheta e^{-|\lambda|\alpha} \cos \lambda z d\lambda \right] = \lim_{\alpha \to 0} \left[\frac{2\pi a}{R} \int_{0}^{\infty} e^{-|\lambda|\alpha} \lambda B(\lambda) K_1(\lambda a) \cos \lambda z d\lambda \right],$$

so that

$$\frac{\vartheta}{\pi} = \frac{2\pi a}{R} B(\lambda) \lambda K_1(\lambda a),$$

or

$$B(\lambda) = \frac{\vartheta R}{2\pi^2 a [\lambda K_1(\lambda a)]}. \tag{10}$$

Using this expression for $B(\lambda)$ in (2), we find

$$V = \frac{\vartheta R}{2\pi^2 a} \int_{0}^{\infty} \frac{K_0(\lambda r)}{\lambda K_1(\lambda a)} \cos \lambda z d\lambda.$$

In logging problems, we are mainly interested in values of the potential along the surface of the sonde, which means at $r=a$, and we have

$$V_{r=a} = \frac{\vartheta R}{2\pi^2 a}\int_0^\infty \frac{K_0(\lambda a)}{\lambda K_1(\lambda a)} \cos \lambda z d\lambda. \tag{11}$$

An efficient method of obtaining numerical solutions of this type of integral has been presented recently (de Witte and Fournier, 1959).

POTENTIAL FIELD DUE TO A FINITE CYLINDRICAL ELECTRODE ON AN INSULATING SONDE

Consider a cylindrical electrode of length $2L$ with its center at the origin and its longitudinal axis along the z-axis (see Figure 2). Let the diameter of the electrode be equal to $2a$.

Numerical solutions of equation (11) give values of the potential, V_z, along the surface $r=a$ due to an infinitely thin ring located in the plane through the origin, perpendicular to the z-axis.

Let us think of the electrode as divided into $2n+1$ slices of equal thickness

$$h = \frac{2L}{2n+1}.$$

The current leaving the central ring be ϑ_0, that leaving each one of the immediately adjacent rings ϑ_1, etc., and the current leaving each one of the outer rings be ϑ_n. In calculating the potential at one ring due to any other ring we assume the potential to be measured at the median plane of the ring and all currents to leave from the median planes of the other rings. The error due to this approxima-

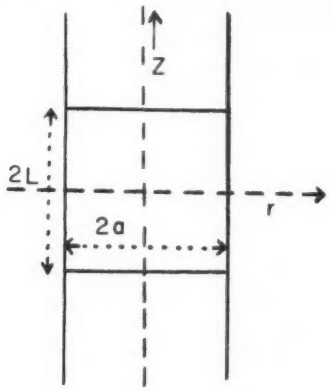

FIG. 2. Schematic of a finite cylindrical electrode of length $2L$, mounted on an insulating sonde of the same diameter.

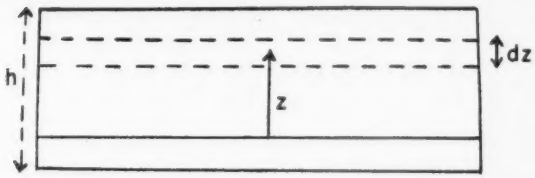

FIG. 3. A single ring with homogeneously distributed current density.

tion can be made arbitrarily small by choosing n, sufficiently large. Let the normalized potential at distance z from a ring carrying unit current be denoted by $\overline{V}_z$. The potential, V_i, at the ith ring will be found by superposition of the potentials due to all the rings and will, therefore, be given by

$$V_i = \vartheta_0 \left[\sum_{j=1}^{n} \frac{\vartheta_j}{\vartheta_0} (\overline{V}_{|i-j|h} + \overline{V}_{(i+j)h}) + \overline{V}_{ih} \right]. \tag{12}$$

From equation (11) we can deduce that $V_z \to \infty$ as $z \to 0$. The potentials V_0 and $(\overline{V}_{|i-j|h})_{i=j}$ need therefore special consideration: To find the potential at a thin ring due to the current emitted by the ring itself we assume that the current density is homogeneously distributed over all of the surface of the ring (see Figure 3).

We now think the ring divided into an infinite number of infinitely thin slices of width dz. If the total current from the ring is i_j and the total width of the ring is h, then the current emitted by each slice will be $(dz/h)i_j$.

At a circle at distance z from the slice dz we can calculate the potential due to this current from (11)

$$dV = \frac{dz}{h}\, i_j\, \frac{R}{2\pi^2 a} \int_0^\infty F(x) \cos\left(\frac{z}{a}\, x\right) dx \tag{13}$$

where $x = \lambda a$ and for a homogeneous medium

$$F(x) = \frac{K_0(x)}{xK_1(x)}\,.$$

The potential due to all slices of the finite ring will be of the form:

$$V = \frac{Ri_j}{2\pi^2 ah} \int_0^\infty \int F(x) \cos\left(\frac{z}{a}\, x\right) dz dx. \tag{14}$$

In (14) the limits of integration with respect to z have not been specified. They depend on the choice of the position of the reference circle at which the potential is calculated. If this circle is at a distance z_1 from the end of the ring, then the integration is carried out from 0 to z_1 and from 0 to $(h - z_1)$ so that (14)

yields

$$V = \frac{Ri_j}{2\pi^2 h}\left[\int_0^\infty \frac{F(x)}{x} \sin\left(\frac{z_1}{a}\, x\right) dx + \int_0^\infty \frac{F(x)}{x} \sin\left(\frac{h - z_1}{a}\, x\right) dx\right]. \tag{15}$$

We can choose z_1 as one half of the distance between the center and the end of the ring or we can average the result of (15) for a number of possible values of z_1. The variation in V due to the choice at this point will become smaller as h becomes smaller.

Since all of the electrode surface must be at the same potential, we have the conditions:

$$V_0 = V_1 = \cdots = V_i = \cdots = V_n, \tag{16}$$

which gives a total of n simultaneous equations of the form:

$$\sum_{j=1}^{n} \frac{g_j}{g_0} (\overline{V}_{|i-j|h} + \overline{V}_{(i+j)h} - 2\overline{V}_{jh}) = \overline{V}_0 - \overline{V}_{ih}. \tag{17}$$

These n simultaneous equations can be solved for the n unknown quantities $x_j \equiv g_j/g_0$ (j from 1 to n).

The total current g is then given by

$$g = g_0\left(1 + 2\sum_{j=1}^{n} \frac{g_j}{g_0}\right), \tag{18}$$

from which we find

$$g_0 = \frac{g}{1 + 2\sum_{j=1}^{n}\left(\frac{g_j}{g_0}\right)}$$

and each of the individual currents are given by

$$g_j = g_0 x_j.$$

Finally, the potential of the electrode is equal to $V_0 = V_i$ or

$$V = g_0\left[\sum_{j=1}^{n}\left(2\,\frac{g_j}{g_0}\,\overline{V}_{jh}\right) + \overline{V}_0\right]. \tag{19}$$

The electrode impedance R_e is

$$R_e = \frac{V}{g} = \frac{\sum_{j=1}^{n}\left(2\,\frac{g_j}{g_0}\,\overline{V}_{jh}\right) + \overline{V}_0}{1 + 2\sum_{j=1}^{n}\left(\frac{g_j}{g_0}\right)}. \tag{20}$$

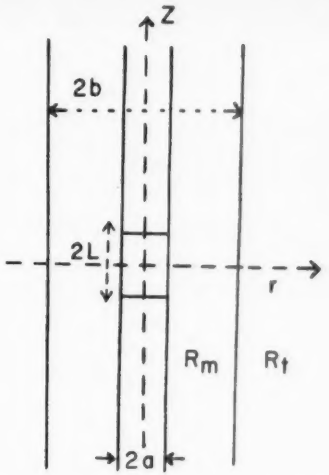

FIG. 4. Schematic of a cylindrical electrode on an insulating sonde located coaxially in a cylindrical borehole.

The potential at the surface of the sonde at a distance z_0 from the median plane of the finite electrode will be given by

$$V = \sum_{k=-n}^{n} \frac{\vartheta_k R}{2\pi^2 a} \int_0^\infty \frac{K_0(\lambda)}{\lambda K_1(\lambda)} \cos \lambda z_k d\lambda, \tag{21}$$

where

$$\vartheta_k = \vartheta_{-k} = \frac{\vartheta x_k}{1 + 2\sum_{j=1}^{n} x_j} \quad \text{and} \quad z_k = z_0 + kh.$$

POTENTIAL FIELD OF A FINITE CYLINDRICAL ELECTRODE LOCATED COAXIALLY IN A BOREHOLE

We shall derive the potential distribution for the case where the insulating sonde on which the electrode is mounted is located coaxially in an infinite cylindrical borehole, of radius b, surrounded by a homogeneous medium of resistivity R_t (see Figure 4).

Let the borehole be filled with a fluid of resistivity R_m, and let V_1 denote the potential inside the borehole and V_2 the potential outside the borehole. Both V_1 and V_2 will be of the general form of equation (1). Since V_2 must go to zero for

infinite r, the coefficient of the I_0 term in its integrand must be zero and we have

$$V_2 = \int_0^\infty B_2(\lambda) K_0(\lambda r) \cos \lambda z d\lambda. \tag{22}$$

Since V_1 is present only in the region where $a \leq r \leq b$ both the I_0 and K_0 terms are permitted in its general solution so that

$$V_1 = \int_0^\infty [A_1(\lambda) I_0(\lambda r) + B_1(\lambda) K_0(\lambda r)] \cos \lambda z d\lambda. \tag{23}$$

We now can apply the following boundary conditions: at $r = a$ we have as before

$$\mathcal{I}\delta(z) = -\frac{1}{R_m}\left(\frac{\partial V_1}{\partial r}\right)_{r=a} 2\pi a. \tag{24}$$

Differentiating (23) under the integral sign and substituting gives*

$$\mathcal{I}\delta(z) = -\frac{2\pi a}{R_m}\int_0^\infty [A_1(\lambda) I_1(\lambda a) - B_1(\lambda) K_1(\lambda a)] \cos \lambda z d\lambda.$$

This reduces, by the method outlined in the previous section, to

$$\lambda[A_1(\lambda) I_1(\lambda a) - B_1(\lambda) K_1(\lambda a)] = -\frac{\mathcal{I} R_m}{2\pi^2 a}. \tag{25}$$

At the boreface we have two boundary conditions. First the potential must be continuous at the boreface, which is expressed by

$$(V_1)_{r=b} = (V_2)_{r=b}.$$

Substitution of relations (22) and (23) gives

$$\int_0^\infty [A_1(\lambda) I_0(\lambda b) + B_1(\lambda) K_0(\lambda b)] \cos \lambda z d\lambda = \int_0^\infty B_2(\lambda) K_0(\lambda b) \cos \lambda z d\lambda.$$

Since this condition holds for all values of z we can equate the integrands, so that

$$A_1(\lambda) I_0(\lambda b) + B_1(\lambda) K_0(\lambda b) = B_2(\lambda) K_0(\lambda b). \tag{26}$$

The second boundary condition at the boreface is that the normal component of current density must be continuous (the amounts of current entering and

* We use here the properties

$$\frac{dI_0(r)}{dr} = I_1(r) \quad \text{and} \quad \frac{dK_0(r)}{dr} = -K_1(r).$$

leaving the boundary must be equal). This is expressed by

$$\frac{1}{R_m}\left(\frac{\partial V_1}{\partial r}\right)_{r=b} = \frac{1}{R_t}\left(\frac{\partial V_1}{\partial r}\right)_{r=b}.$$

Substitution of relations (22) and (23) and equating the integrands yields:

$$\frac{1}{R_m}\left[A_1(\lambda)I_1(\lambda b) - B_1(\lambda)K_1(\lambda b)\right] = -B_2(\lambda)K_1(\lambda b)\frac{1}{R_t}. \tag{27}$$

Equations (24), (26), and (27) represent three linear equations in the three unknowns $A_1(\lambda)$, $B_1(\lambda)$ and $B_2(\lambda)$. Since we are interested only in the potential inside the borehole we want to solve these for $A_1(\lambda)$ and $B_1(\lambda)$. We find

$$A_1(\lambda) = \frac{\mathcal{I}R_m}{2\pi^2 a}\left[\frac{(c/\lambda)M_b}{-cI_1M_b + K_1P_b + (c+1)K_1Q_b}\right]$$

and

$$B_1(\lambda) = \frac{\mathcal{I}R_m}{2\pi^2 a}\left[\frac{P_b + (c+1)Q_b}{\lambda(-cI_1M_b + K_1P_b + (c+1)K_1Q_b}\right],$$

where

$$I_1 \equiv I_1(\lambda a), \qquad K_1 \equiv K_1(\lambda a),$$
$$M_b \equiv \lambda b K_0(\lambda b)K_1(\lambda b), \qquad P_b \equiv \lambda b I_0(\lambda b)K_1(\lambda b),$$
$$Q_b \equiv \lambda b I_1(\lambda b)K_0(\lambda b), \qquad \text{while } c = R_t/R_m - 1.$$

Substituting the above values of $A_1(\lambda)$ and $B_1(\lambda)$ into equation (23) we obtain for $r=a$

$$V_1 = \frac{\mathcal{I}R_m}{2\pi^2 a}\int_0^\infty \frac{cP_aM_b + M_aP_b + (c+1)M_aQ_b}{a\lambda^2K_1(-cI_1M_b + K_1P_b + (c+1)K_1Q_b}\cos\lambda z d\lambda,$$

where

$$M_a = \lambda a K_0(\lambda a)K_1(\lambda a) \text{ etc.}$$

This expression can be further simplified by using the Wronskian equality $P+Q=1$ which gives [Smythe, 1950, p. 187, equation 5.32 (7)]:

$$(V_1)_z = \frac{\mathcal{I}R_m}{2\pi^2 a}\int_0^\infty \frac{K_0[M_a + cM_b + c(M_aQ_b - Q_aM_b)]}{\lambda K_1[c(M_aQ_b - Q_aM_b) + M_a]}\cos\lambda z d\lambda. \tag{28}$$

Now let $\lambda a = x$ and $b/a = m$; then

$$(V_1)_z = \frac{\mathcal{I}R_m}{2\pi^2 a}\int_0^\infty \frac{K_0[M + cM_m + c(MQ_m - QM_m)]}{xK_1[M + c(MQ_m - QM_m)]}\cos xs dx, \tag{29}$$

where

$$M \equiv M(x) \text{ etc.}, \qquad Q_m \equiv Q(mx) \text{ etc.},$$

and $s=z/a$ (spacing expressed in sonde diameters).

We note that if in equations (28) and (29) we set $c=0$, which implies $R_t=R_m$, the expressions for the potential reduce to equation (11) which was derived for the case of a homogeneous medium surrounding the electrode.

Relations (28) and (29) give the potential at the surface of the sonde at any distance z (or s) from the infinitely thin current ring.

The potential at some point on the surface of the sonde due to a finite cylindrical electrode whose median plane is at a distance z_0 from the point in question is found by the same procedure as that described for the homogeneous case. The potential is given by a relation of the type of (21) with the integral of the form of (28).

NUMERICAL EXAMPLES

Table I shows the values of the potential V_z measured at the surface of an insulating sonde at a distance of 16 inches from the median plane of a cylindrical

TABLE I

$R_2=R_1$ $z_0=16$ inches $a=1.625$ inches $L=2$ inches $\mathcal{I}=1$ amp.

V_z (volts)	n	V_{z_0} (volts)
.18942	2	.188402
.18948	3	.188402
.18950	4	.188402
.18952	5	.188402
.18953	6	.188402
.18953	7	.188402
.18953	8	.188402
.18954	9	.188402
.18954	10	.188402
.18954	11	.188402
.18954	12	.188402

electrode 4 inches long, with a 3.25-inch diameter. The sonde diameter is also 3.25 inches. The calculated V_z are listed for increasing values of n.

The number of rings into which the electrode is divided is $2n+1$. We note that for values of n larger than 4 or more than 9 rings, the potential in this case is within 0.02 percent of the asymptotic value reached for large n. The potential, V_{z_0}, calculated on the assumption that all the current is emitted from the median plane, is smaller than the asymptotic value by less than 0.6 percent.

Table II shows the same data, with n incremented in steps of 2 for the same electrode and sonde, located on the axis of a cylindrical hole, with a hole diameter

TABLE II

$R_2=30R_1$	$z_0=16$ inches	$a=1.625$ inches	$L=2$ inches	$\mathcal{I}=1$ amp.
V_z (volts)		n	V_{z_0} (volts)	
6.946298		2	6.932054	
6.947303		4	6.932054	
6.947440		6	6.932054	
6.947481		8	6.932054	
6.947578		10	6.932054	

equal to two times the sonde diameter and the resistivity of the surrounding medium equal to 30 times the resistivity of the material filling the hole.

Table III shows a comparison between the asymptotic V_z and the potential V_{z_0} (all current emitted from median plane) for an electrode with $L/a=1$, for measurements made at various distances from the sonde in a homogeneous medium. It can be seen that the median plane approximation is good (± 0.5 percent) as long as the distance at which the potential is measured is large com-

TABLE III

$L/a=1$	$R_1=R_2$	$\mathcal{I}=1$ amp.	$n=10$
z_0/a	V_z (volts)		V_{z_0} (volts)
1.05	1.57289		1.15867
1.25	1.24519		1.03191
2.0	0.79766		0.74186
4.0	0.43453		0.42542
8.0	0.23013		0.22893
40.0	0.04780		0.04800

pared to the half length of the electrode ($z \geq 8L$). At shorter distances the error rapidly increases. At 1/20 of the half length from the edge of the electrode, the median plane approximation gives a potential value, which is about 25 percent below the actual value.

Table IV shows data for a longer electrode ($L/a=4$). We note that a larger value of n has to be used in order to approach the asymptotic value of V_z to within a given accuracy. The closer the point of measurement is to the edge of the electrode, the larger the difference between V_z and V_{z_0} and the larger the required value of n for given precision in V_z. For the case where the point of measurement is only 1/64 half-length from the electrode edge, the asymptotic value of V_z is not quite reached even at $n=20$.

Table V lists values of V_{z_0} and V_z for a probe located on the axis of a cylindrical hole with a diameter equal to twice the probe diameter for various resistivity contrasts between the medium inside the hole and that outside the hole. We see that

TABLE IV

$R_1=R_2$	$L/a=4$	$\mathcal{I}=1$ amp.
	$z_0/a=4.0625$ inches	
V_z (volts)	n	V_{z_0} (volts)
.635950	2	.419741
.695424	4	.419741
.721571	6	.419741
.739109	8	.419741
.750010	10	.419741
.757687	12	.419741
.763387	14	.419741
.767290	16	.419741
.770139	18	.419741
.773282	20	.419741
	$z_0/a=8$ inches	
.251293	2	.228931
.253190	4	.228931
.253688	6	.228931
.253893	8	.228931
.253986	10	.228931
.254027	12	.228931
.254050	14	.228931
	$z_0/a=40$ inches	
.047485	2	.048001
.047485	4	.048001
.047486	6	.048001
.047487	8	.048001
.047487	10	.048001

TABLE V

$L/a=1$	$z_0/a=1.25$	$\mathcal{I}=1$ amp.
R_2/R_1	V_z (volts)	V_{z_0} (volts)
1	1.2452	1.0319
30	13.0448	12.8727
300	53.6709	53.5216

the percentage difference between V_{z_0} and V_z decreases as the resistivity contrast increases. This result is to be expected, since at the higher resistivity contrasts the hole itself starts acting as a shunt, which reduces the influence of size or shape of the electrodes.

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GEOPHYSICS, VOL. XXIV, NO. 3 (JULY, 1959), PP. 580–597, 8 FIGS.

SEISMIC VELOCITY DATA FROM TRINIDAD, B.W.I., AND COMPARISON WITH THE CARIBBEAN AREA*

G. E. HIGGINS†

ABSTRACT

The results of the velocity surveys made on four deep (± 10,000 ft) wells in Trinidad are reported, together with summaries of the lithologic and stratigraphic data recorded by the wells. An unusual velocity inversion of 5,000 ft/sec between 2,500 and 5,000 ft depth is reported in one well, Moruga 15. The recorded data from the well surveys and from refraction surveys shot near the metamorphosed Northern Ranges in Trinidad are compared with published data reported by Worzel, Ewing, et al. in their refraction surveys within the Caribbean Sea, the Venezuelan waters near Trinidad, and Barbados. Comparison is also made with the results of refraction surveys in British and Dutch Guiana.

INTRODUCTION

This report reviews the velocity data from four deep wells surveyed in Trinidad, B.W.I., during 1951–1955 (Figure 1). One of these wells, Mt. Harris No. 1, is located in the Central Range area of Trinidad, while the remaining three are located in the South Trinidad oil belt. After a discussion of the Trinidad data, certain published and other known information concerning seismic velocities in Trinidad and nearby areas is presented for further comparison.

The reader is referred to the publications of Suter (1951–1952) and Kugler (1953, 1956) for a review of the geological background of Trinidad and the wells under discussion.

Mt. Harris Well 1.

This well (Figure 1, Well 1) is located in the Central Range area of Trinidad where Cretaceous rocks outcrop at the surface. The Central Range comprises one of the older structural units of Trinidad and it was anticipated that high velocities might be found here. The well penetrated Upper Cretaceous beds at about 1.14 km (3,750 ft) sub-sea and Lower Cretaceous (Barremian?) at 1.47 km (4,800 ft) sub-sea, remaining in this formation to final depth 3.26 km (10,695 ft). The Lower Cretaceous formation occurs as a fairly uniform series of hard shales, dominantly non-calcareous with occasional interbedded quartzitic sandstone layers which are generally thin but may be up to 45 m (150 ft) thick.

The average velocity data is shown plotted on Figure 2 while Figure 3 shows the plot of t_c against z_c where

z_c = depth of well geophone below datum (mean sea-level),
t_c = corrected arrival time at well geophone.

The *average velocity curve* shows an almost linear increase in velocity with

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FIG. 1. Location map.

depth from 1.47 km (4,800 ft), where there is a corresponding change in slope on the z_c/t_c plot. At $t_c = 1.0$ sec the indicated velocity is 3.4 km/sec (11,250 ft/sec).

The interval velocity data are shown on Figure 4 together with pertinent information on lithology, dip, and density. The interval velocities show a

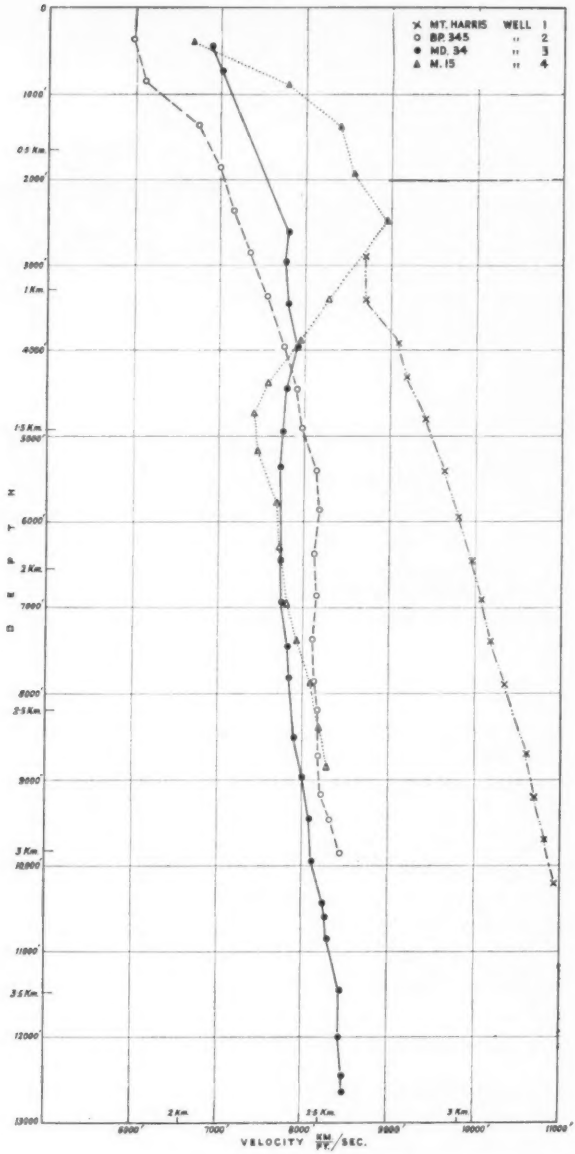

FIG. 2. Depth vs. average velocity.

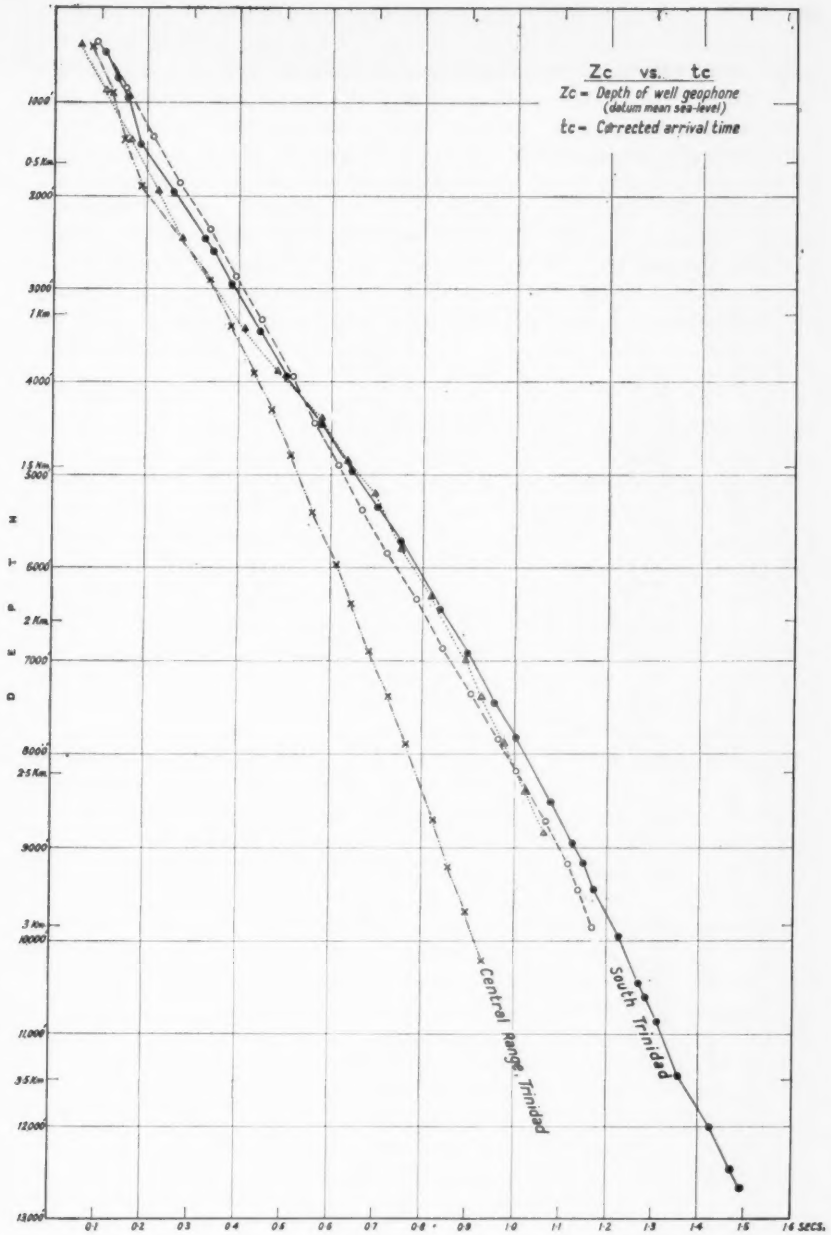

FIG. 3. Plot of z_c against t_c.

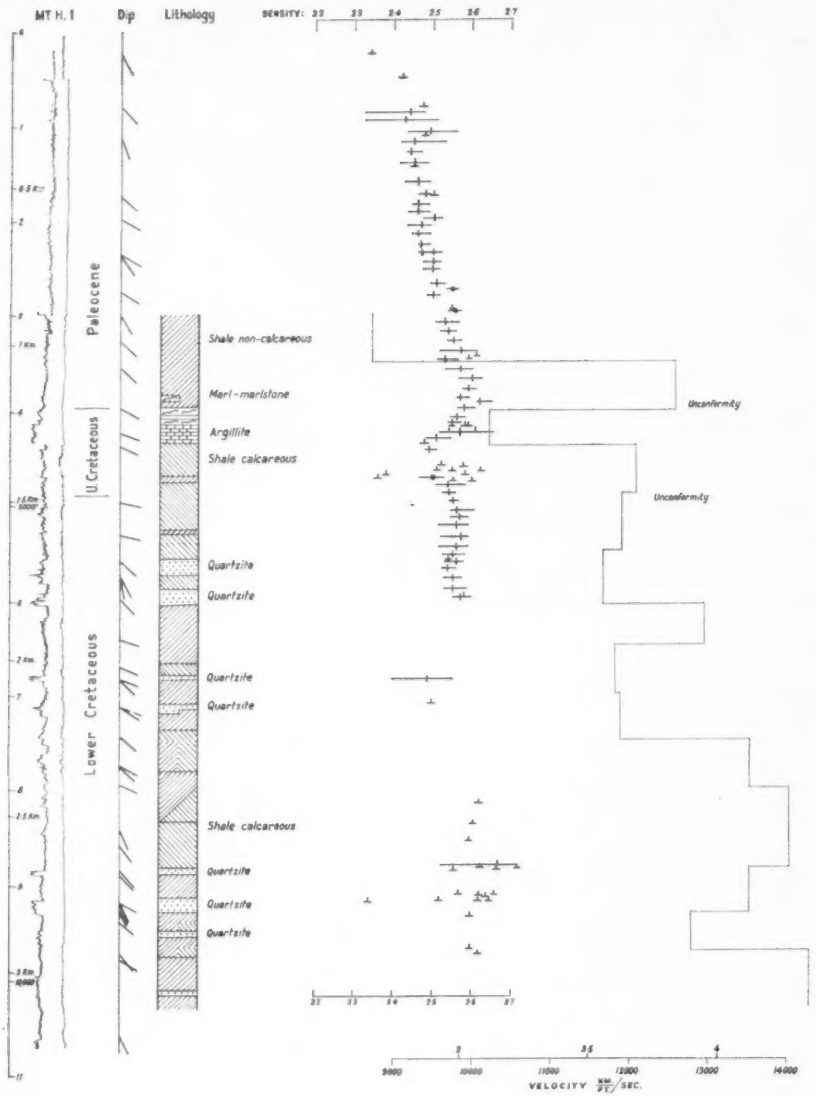

FIG. 4. Mount Harris Well No. 1.

fluctuating but gradual increase with depth. The reduced velocity in the Upper Cretaceous argillite section at 1.25–1.34 km (4,100 to 4,400 ft) is a frequent characteristic of this formation even in South Trinidad. The argillite is a siliceous to cherty siltstone, slightly calcareous in parts, and with occasional thin shale layers. The quartzites and quartzitic sandstones generally show lower velocities than the interbedded shales. The density data are fairly good from 0.30 to 1.83 km (1,000 to 6,000 ft) but scattered below that depth. There is a gradual increase in density over that range, but no obvious relationship with interval velocity is apparent. The range of density values at any interval is less than that seen in the South Trinidad wells, suggesting greater consolidation of sediments in the Central Range area.

Barrackpore 345

This well (Figure 1, Well 2) lies on the north flank of the Siparia syncline and is about 18 km (11 miles) south of the Central Range structure. The well penetrated an alternating sequence of sands and shales of the Upper to Middle Miocene (Forest and Cruse formations) from 0.30 km to 1.67 km (1,000 ft to 5,480 ft). Below 1.67 km the well drilled through a thick series of homogeneous clays of Lower Cruse age to 2.80 km (9,200 ft), while below this depth lithology indicates changing conditions to shales, gritty and pebbly shales, and sandstones (Herrera) of the Lower Miocene Karamat and Cipero formations.

The *average velocity* data, Figure 2, shows an almost linear increase with depth from below 0.30 km to 1.65 km (1,000 ft to 5,400 ft). and then remains fairly constant to 2.80 km (9,200 ft) when a gradual increase occurs to bottom.

The z_c/t_c plot, Figure 3, is almost linear from surface to 2.80 km (9,200 ft) with the exception of values between 1.37 and 2.07 km (4,500 ft to 6,800 ft). At $t_c = 1.0$ sec the indicated velocity is 2.5 km/sec (8,200 ft/sec).

The *interval velocity* data and well log are given in Figure 5 and the velocity shows a steady increase from surface to the base of the dominantly sandy formations at 1.65 km (5,480 ft). From 1.65 km to 2.80 km (5,480 ft to 9,200 ft) the recorded interval velocities are less in a fairly homogeneous shale section. There is a sharp increase in velocities below 2.80 km (9,200 ft) with the appearance of pebbly and gritty shales, sands, and sandstones.

It is noted that frequent reflections are recorded in the upper sandy intervals down to 1.65 km (5,480 ft) and again below 2.80 km (9,200 ft) in the deeper sandy zones. Reflections are rare to nil in the intervening shaly zone, although the interval velocities show contrasts equal to those of the upper sandy horizons.

No density data are available from this well, but average data from nearby wells has indicated a fairly wide range of densities (2.0 to 2.4) in the upper sandy formations with the shales below indicating a gradual increase in density with depth, range 2.1 to 2.35, while the deeper Lower Miocene Karamat-Cipero formations show maximum densities (range 2.35 to 2.50).

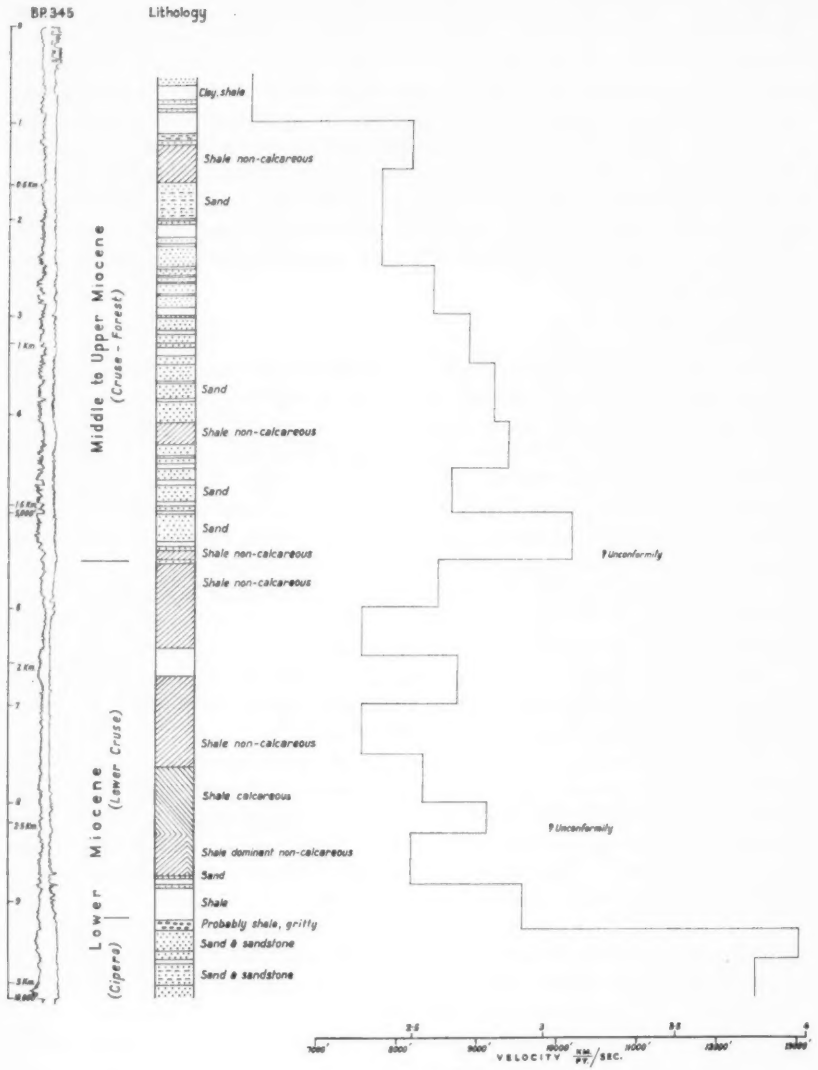

FIG. 5. Barrackpore Well No. 345.

Morne Diablo Well 34.

This well (Figure 1, Well 3) lies on the south flank of the Siparia syncline and is about 3.3 km (2 miles) south of Barrackpore Well 345. The well commenced drilling in the Cruse Formation (Middle Miocene) and was completed in Upper Cretaceous sands and shales at 4.32 km (14,018 ft). From surface to 2.59 km (8,500 ft) depth the lithology is almost wholly shale with rare sandy streaks of the Cruse and Karamat formations. Cipero (Lower Miocene) sands are developed between 2.59 and 2.68 km (8,500 and 8,800 ft) and thereafter the well penetrated a sequence of alternating non-calcareous and calcareous shale to 3.26 km (10,700 ft) with dominantly calcareous shales (marls-marlstones) below that depth to 3.65 km (12,000 ft) where top Paleocene was found. Upper Cretaceous argillite with some shales was penetrated at 3.8 km (12,500 ft), while from 3.96 km (13,000 ft) to bottom, at 4.32 km, a thick sequence of sands with subordinate interbedded silts and conglomerates was found. No velocity data were recorded below 3.85 km (12,650 ft) however.

Cable breaks are suspected on the records above 0.79 km (2,600 ft), but below that depth to 2.59 km (8,500 ft) the *average velocity* (Figure 2) curve remains almost constant with even a slight reduction. Below 2.59 km (8,500 ft) the curve shows a gradual and almost linear increase in velocity to 3.49 km (11,450 ft) with a decreasing velocity gradient below that depth to bottom. The break at 3.49 km (11,450 ft) probably corresponds to a change in the calcareous carbonate content of what appears otherwise as a fairly uniform shale lithology. There are significant changes in the gamma-ray and electric logs at this point, but there are no cores to establish if other important lithologic differences are present.

The z_c/t_c plot (Figure 3) is slightly curved with the most significant change in slope at 3.49 km (11,450 ft).

At $t_c = 1.00$ secs the average velocity is 2.38 km/sec (7,800 ft/sec).

In regard to the *interval velocity* data (Figure 6) a slight increase in interval velocities is seen below 0.79 km (2,600 ft) to 1.22 km (4,000 ft) followed by a decrease. Thereafter an almost constant velocity to 1.77 km (5,800 ft) is followed by a gradual increase in velocity to the top of the sandy zone at 2.59 km (8,500 ft). The recorded densities throughout the interval discussed are few but indicate a gradual increase in density with depth. The lower density values at 2.59 km are of porous sands, and the higher are of intervening shale samples. Below 2.59 km a slight increase in interval velocity occurs to 3.05 km (10,000 ft) followed by considerable variations in velocity, of up to 1.2 km/sec (4,000 ft/sec) in a sequence of calcareous and non-calcareous shales and marls of Oligocene and Eocene age. No density data are available in this interesting part of the section.

Near-the-well reflections are rarely recorded in the interval from surface to 1.22 km (4,000 ft) but do appear northward in greater quantity suggesting changing lithologies (i.e., possibly more arenaceous developments) in that direction. Reflections are also rare in the shaly section from 1.22 km (4,000 ft) to

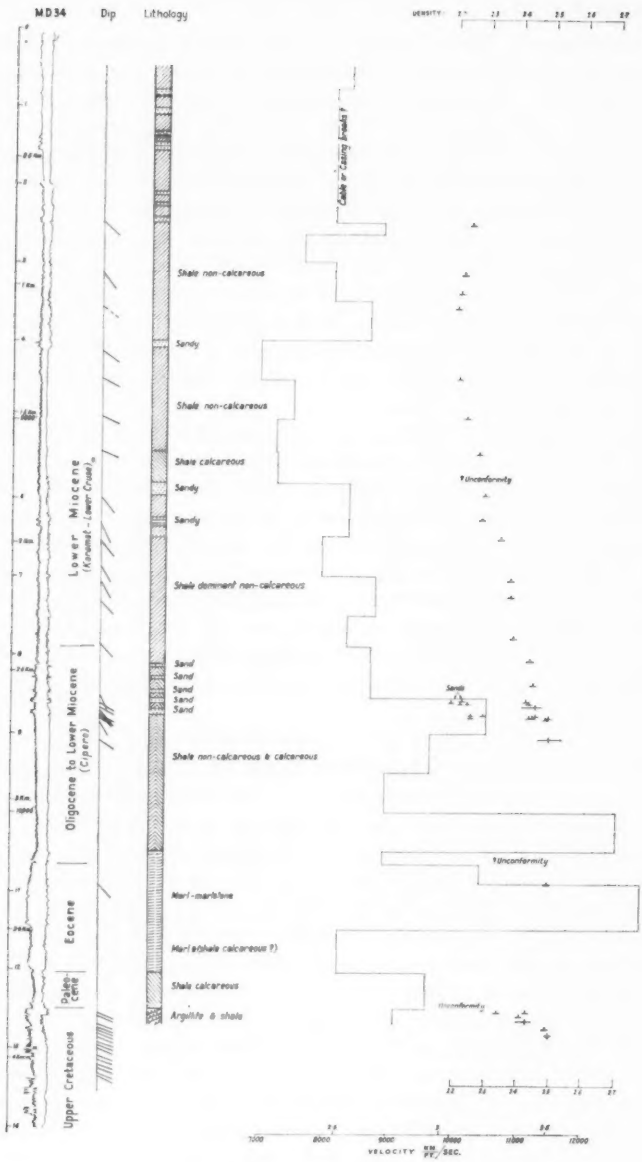

FIG. 6. Morne Diablo Well No. 34.

2.59 km (8,500 ft) but are often recorded at the level of the sandy zone at 2.59 km. Fair reflections are also recorded in the zone of very contrasting interval velocities between 3.05 km (10,000 ft) and 3.96 km (13,000 ft), and from the alternating sequence of sands and shales found below 3.96 km.

Moruga Well 15.

This well lies 23 km (14 miles) to the east of Morne Diablo 34 and was shot in anticipation of higher average velocities at depth in this part of South Trinidad (Figure 1, Well 4). The well commenced drilling in Miocene sands and silts but penetrated a much reduced sequence of Miocene and older formations to find the Upper Cretaceous argillite and calcareous shales at 1.43 km (4,700 ft). This lithology gave way to a series of sands, sandstones, and silts with frequent conglomeratic and gritty zones with occasional shales at 2.12 km (6,950 ft) sub-sea to the bottom of the well. The well is remarkable in showing higher velocities at shallower depths than were expected, followed by an unusual velocity inversion which brought back the average velocity data into line with results obtained in the other wells shot in South Trinidad.

The *average velocity* curve (Figure 2) shows a pronounced decreasing velocity gradient between 0.75 km (2,450 ft) and 1.43 km (4,700 ft) in a sequence of calcareous and non-calcareous shales of Lower Miocene and Paleocene age. As noted the top of the Cretaceous occurs at 1.43 km and an increasing velocity gradient can be seen from 2.12 km (6,950 ft) corresponding to the marked lithologic change in the Cretaceous formations.

The z_c/t_c (Figure 3) plot appears as a very flat sigmoidal curve with the main changes of slope at 1.52 km (5,000 ft) and 2.13 km (7,000 ft) corresponding to the lithologic and formation changes described above.

The *interval velocity* data of this curve are shown in Figure 7, together with other pertinent data and well log, and are remarkable in showing some unusual contrasting values. Between 1.22-km (4,000-ft) and 1.52-km (5,000-ft) depths the velocities are lower than the elevation velocity used for elevation correction. A well defined velocity inversion occurs between 0.76 km (2,500 ft) and 1.52 km (5,000 ft) in a sequence of shales which are occasionally calcareous, of Miocene to Paleocene age. Dips are uniform throughout and, as in all well surveys made, there appears to be no discernible relationship between dip and the velocity data. Some of the cores indicated fractured and squeezed conditions but others appeared undisturbed. The density data show a wide range in values generally decreasing between 1.06 km (3,500 ft) and 1.61 km (5,300 ft) but increasing from 1.61 km to bottom. The densities are of dry specimens and too few for reliable averaging, but the described trend seems fairly clear. The Cretaceous section below 1.52 km (5,000 ft) shows variable interval velocities, being conspicuously higher between 1.65 km (5,400 ft) and 1.82 km (6,000 ft), and below 2.13 km (7,000 ft). It has frequently been noted that the uppermost part of the "argillite" of the Cretaceous formation is invariably more fractured, of low density, and has a

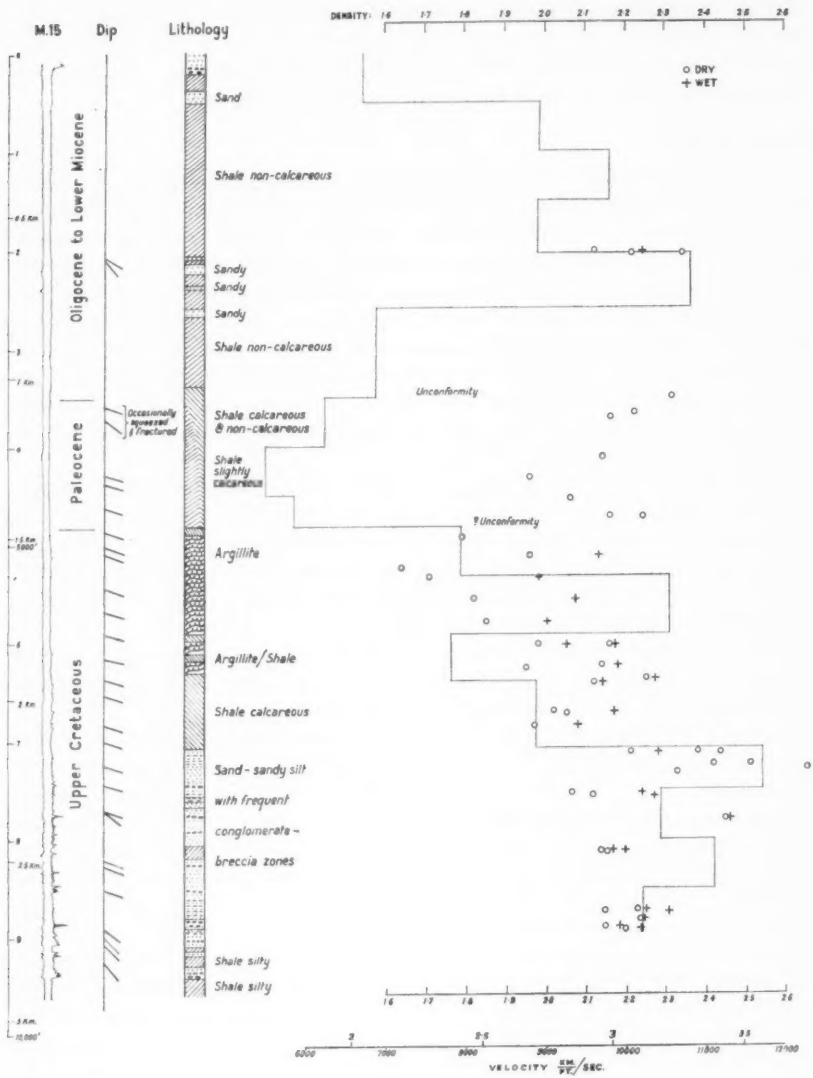

FIG. 7. Moruga Well No. 15

weathered appearance, probably related to the major unconformity at the top of the Cretaceous, and these factors likely account for the low velocity in this interval followed by the higher values in the remaining and lower argillite section. The lithological change from argillaceous to arenaceous character of the sediments from 2.13 km (7,000 ft) is indicated by substantially higher velocities in the arenaceous formations.

It is noteworthy that this district has given some of the best reflection data ever recorded in South Trinidad, an area which as a whole is one of poor seismic response. Reflections are particularly abundant from the interval below the top Cretaceous to 2.44 km (8,000 ft), and exhibit for South Trinidad, unusual amplitude and character.

Interval Velocity of Miocene Cruse Shales and Forest-Cruse Sands

Seventeen wells have been shot throughout Southern Trinidad for velocity data and the interval velocities recorded in the Cruse shales of these wells is plotted in Figure 8. The depths of these shales range from 0.37 km (1,200 ft) to 2.44 km (8,000 ft.).

If the two higher-than-average values at shallow depth are excluded, the plot of values shows a general trend of increasing velocity with depth, despite the tendency towards a rather broad range of velocity for a given depth. However, individual wells may show a velocity inversion of up to 0.46 km/sec (1,500 ft/sec) with depth.

A similar plot (Figure 9) has been prepared for interval velocities in the Miocene Forest-Cruse sands which overlie the aforementioned shales. The intervals in which these velocity determinations were made actually comprise alternations of sands and shales and thus include a variable lithologic factor. Nevertheless a general increase in velocity with depth is again apparent, while depth for depth these "sands" show higher velocities. The approximate percentage of sand in the measured interval is indicated by the small numbers which correspond to 10 percent values (i.e., 4=40 percent).

REFRACTION DATA

Northern Trinidad

A number of refraction profiles were made in North Trinidad near Arima during 1937–1939 (Figure 1). Reversed profiles were shot in all cases with the longest spread covering 7.3 km (24,000 ft). Geophone spacing was 152 m (500 ft), and shots up to 400 lb were fired at about 30 m (100 ft) depth. Refraction breaks were generally good, although no reliable second breaks could be selected.

A refracting horizon was identified in north-south profiles shot near the Northern Range and it was also evident that this horizon marked a limit of reflections. A true velocity of 5.33 km/sec (17,500 ft/sec) was recorded for this refractor. The identity of the refractor has not been confirmed, but it was considered likely to be the same metamorphosed rocks as found in the Northern

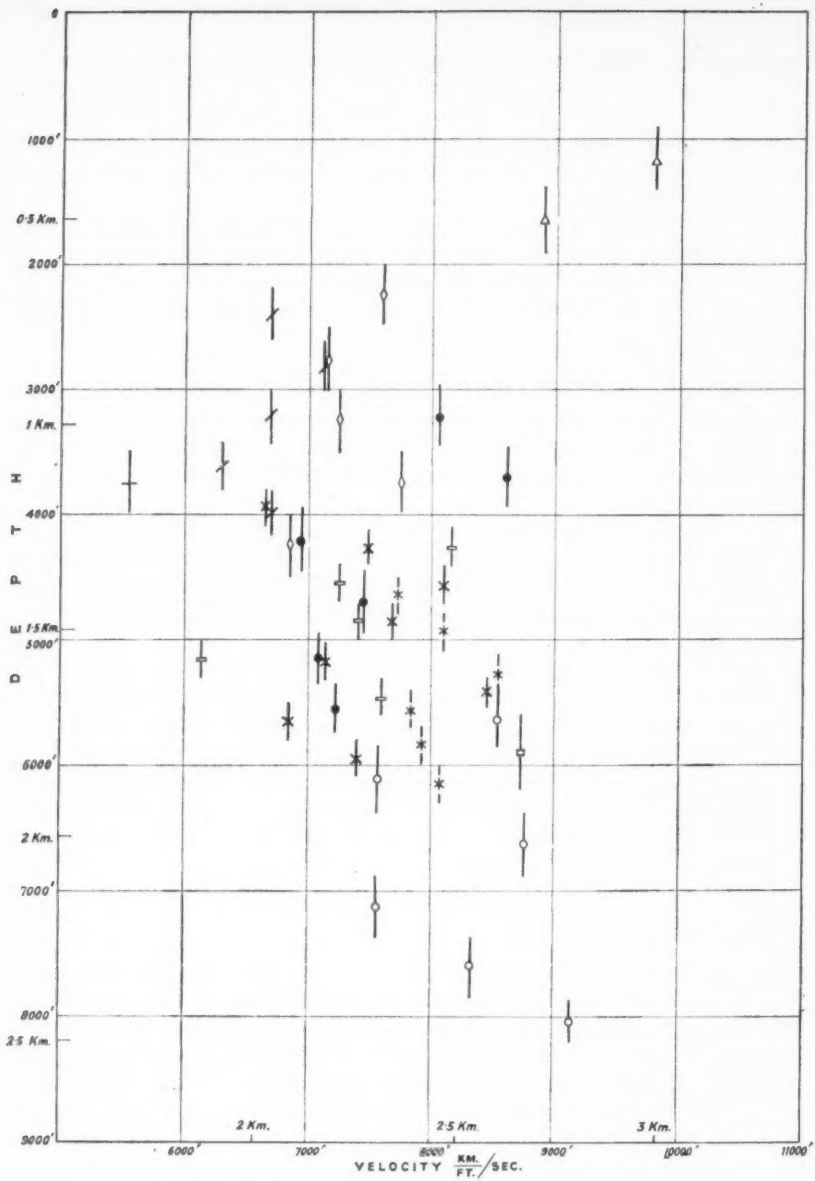

FIG. 8. Interval velocity for similar lithologies and age (Cruse clay).
The different symbols represent different wells.

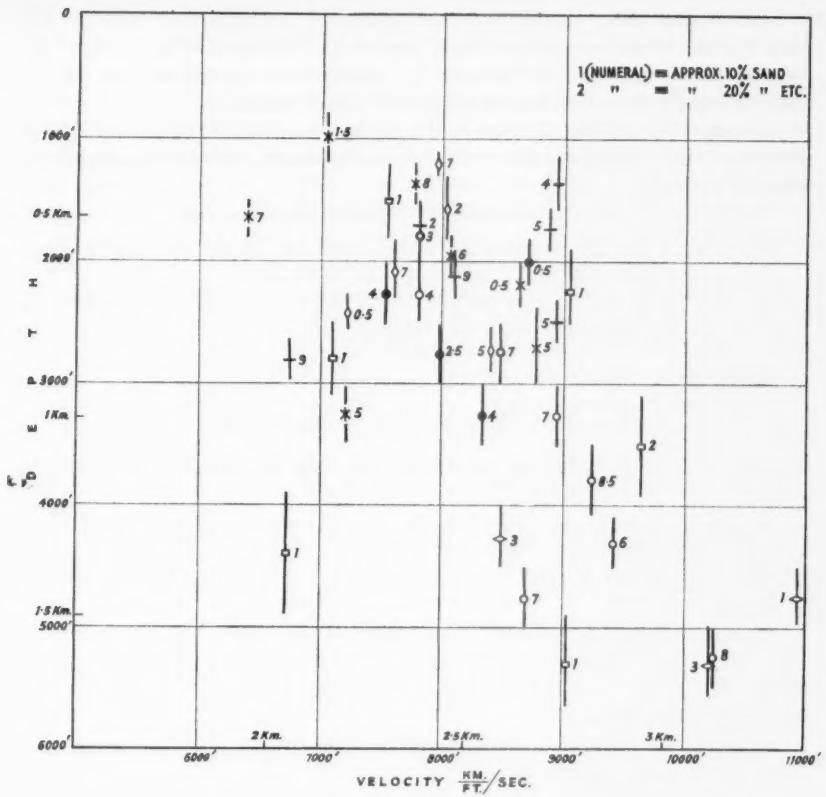

FIG. 9. Interval velocity for Forest-Cruse sands. The different symbols represent different wells.

Range, a not unreasonable belief in view of the proximity of the profiles to this range and general geological considerations.

The highest velocity recorded in the non-metamorphosed Lower Cretaceous formations in the Central Range, Mt. Harris well, is 4.25 km/sec (14,000 ft/sec).

British Guiana

In 1938–1939 the Central Mining & Investment Corporation secured leases over a large section of the coastal regions of Southern British Guiana with a view to oil exploration (Figure 1). Surface mapping was clearly of little value in the superficial deposits covering the coastal plains, and it was necessary to turn to seismic surveys for an understanding of subsurface conditions.

The seismic party carried out both refraction and reflection surveys. The length of the refraction profiles ranged from 5.5 to 7.0 km (18,000 to 23,000 ft) with geophone spacing at 152 m (500 ft). Charges were placed at 25 m (80 ft), and sufficient penetration was recorded with 200 lb explosive.

Results. Although the outcome of the surveys was the drilling of a well, Rose Hall No. 1, on a structural nose defined in the basement, no velocity survey was made in the well.

The refraction surveys determined the following velocities:

V_0=1.6–1.7 km/sec (5,200–5,600 ft/sec) with the lowest velocity recorded where the cover above basement was thickest.

V_b=5.6 to 6.7 km/sec (18,500 to 22,000 ft/sec) and was observed to be smallest where the cover was thickest.

A velocity distribution of

$$V = V_0 + 13.3y^{0.643} \qquad (y = \text{depth in feet})$$

was found to be most satisfactory with a probable discontinuity at V=7,560 ft/sec.

Locally and within the area where the well was drilled a bed of velocity 3.35 km/sec (11,000 ft/sec) was found with an apparent thickness of 380 m (1,250 ft) at one point, and 43 m (140 ft) at another, suggesting convergence on a rising basement.

Based on the seismic surveys it was expected that the well would find basement at 1.9 km (6,300 ft), while the 3.3-km/sec (11,000-ft/sec) bed was expected in the well at 1.65 km (5,400 ft) assuming no masked velocities between this layer and the basement.

The well was drilled to a final depth of 1,968 m (6,456 ft), and details are reported elsewhere (Kugler et al., 1944).

There was good agreement with the seismic surveys, and basement was actually found at 1,956 m (6,420 ft). The 3.3-km/sec bed, which was at one time considered as possibly corresponding to Cretaceous sediments, is related to hard grits and conglomerates found between 1,656 m and 1,738 m (5,434 to 5,700 ft), which grits graded downwards to unconsolidated pebble beds and softer sands. The basement was found overlain by the so-called "superficial deposits" and no true marine Cretaceous or true marine Tertiary was found.

The greatest depth to basement found in the area between the Berbice and Courantyne Rivers was 2.23 km (7,300 ft). The different basement velocities are considered to be related to differences in the basement complex.

During 1939 refraction surveys were also conducted throughout a large area of Dutch Guiana (Surinam), and the reported velocities for basement there are 5.5 to 5.9 km/sec (18,000 to 19,500 ft/sec). A close correspondence with the data recorded in British Guiana is evident.

Orinoco and Gulf of Paria

Worzel and Ewing (1948) have published the results of refraction surveys off the Orinoco River, in the so-called Orinoco shoal in the Gulf of Paria (5, Figure 1) where water depth was 17 m (57 ft), the Orinoco deep (6, Fig. 1) with water depth 36 m (120 ft), and also off Barbados (Figure 1). The summarized results are given below, although it is noted that the data are only of reconnaissance precision and the profiles were not reversed. Some correspondence with Trinidad and Guiana velocity data is suggested.

Orinoco Shoal. The shots were fired in a direction assumed to be perpendicular to the strike, i.e., on a line bearing NNW from the receiving point.

The findings indicated an unconsolidated layer of 1.75-km/sec (5,770-ft/sec) velocity and 565 m (1,860 ft) thick. Below this was found 3,140 m (10,300 ft) of semi-consolidated sediments with velocity of 2.43 km/sec (7,970 ft/sec). At a depth of 3,720 m (12,200 ft) below sea-level a high velocity of 5.15 km/sec (16,890 ft/sec) is reported and considered probably indicative of basement.

The occurrence of this layer at such an unexpectedly shallow depth is of considerable interest from the viewpoint of regional geology. The profile was shot about 19 km (12 miles) west of the Venezuela-Trinidad boundary line in the Gulf of Paria.

Orinoco Deep. Refraction shots were fired here on a line bearing SE. Five layers were defined, although velocity data in the upper three layers indicate gradual changes in velocity, and the column is arbitrarily divided into three zones corresponding to where velocity increases continuously with depth.

The results indicate an unconsolidated layer 500 m (1,640 ft) thick of velocity 1.67 km/sec (5,470 ft/sec) overlying 430 m (1,410 ft) of semi-consolidated material with a velocity of 2.0 km/sec (6,580 ft/sec) which in turn overlies 1.14 km (3,720 ft) of likewise semi-consolidated material of 2.37 km/sec (7,770 ft/sec) velocity. Below the semi-consolidated series is reported 4.85 km (15,900 ft) of consolidated beds with a velocity of 3.43 km/sec (11,250 ft/sec) resting on basement indicated by a velocity of 6.6 km/sec (21,750 ft/sec).

The depth to basement here is therefore 6.95 km (22,800 ft).

Conclusion. In comparison with the data recorded in Trinidad it is suggested that the semi-consolidated layer of 2.38 km/sec corresponds to the Plio-Miocene Tertiaries of South Trinidad, while the higher 3.43 km/sec shows correspondence with Oligocene-Eocene and Cretaceous sediments. The unconsolidated layer of ± 1.7 km/sec is not identified in Trinidad data but is considered likely to represent post-Pliocene sediments.

The basement velocity is higher than any yet recorded in Trinidad, where a maximum value of 5.33 km/sec is suggested for the Northern Range metamorphics.

The velocity of 6.6 km/sec compares with that recorded in the basement of British Guiana, while Heiland (1946) quotes figures of 5.46 km/sec and 6.51

km/sec for igneous basement in Venezuela—although the locality is not known.

Kugler (1953) has reported on the occurrence of gneisses (Dragon gneiss) at the northeast Venezuelan coast (Punta Peña) and has suggested that the Northern Range metamorphics of Trinidad overlie these older basement rocks.

More recently Ewing et al. (1957) have discussed the results of refraction shots over the Trinidad shelf (Figure 1), and their station 24 lies nearest to Trinidad. The velocities recorded at this station may be compared with Trinidad data and suggest that the top of the Northern Range metamorphics, with a recorded velocity 4.8–5.2 km/sec (±16,500 ft/sec), lies at 3.11 km (10,200 ft) below sea level, and it is noted that this layer slopes up sharply southward. Above this layer is reported 1.71 km (5,600 ft) of material of 3.4 km/sec (11,200 ft/sec) velocity, also with a pronounced northward dip, overlain by a thin 370-m (1,200-ft) layer of 2.75 km/sec (9,000 ft/sec) velocity, while this latter also appears to be pinching out southward. An alternative interpretation suggests the two layers may be combined to a single layer of velocity 2.9 km/sec (9,500 ft/sec). These latter velocities are comparable with those recorded in South and Central Trinidad sediments (non-metamorphosed), but volcanic rocks, velocity unknown, are known to occur in nearby Tobago. The uppermost sedimentary layer is 810 m (2,600 ft) thick with velocity ±1.90 km/sec (6,200 ft/sec) and is likely Recent to post-Pliocene material.

Barbados

The seismic data reported from unreversed profiles shot parallel to the shore lines were first reported by Worzel and Ewing (1948), while more recently Ewing et al. (1957) have further extended our knowledge of the Caribbean structure from profiles shot to the north and south of Barbados.

In the immediate area of Barbados an upper unconsolidated layer, 755 m (2,480 ft) thick, and of 1.71 km/sec (5,620 ft/sec) velocity, is indicated overlying 980 m (3,220 ft) of semi-consolidated material with a velocity of 2.75 km/sec (9,030 ft/sec). Below this a more consolidated series of 3.37 km/sec (11,040 ft/sec) velocity is reported. The thickness of this layer could not be determined, and the more recent data have indicated considerable complexity of layering here. It is evident that the high velocity crustal layer must be at some considerable depth, and the data lend support to the concept of a great down-buckle, syncline, or tectogene in the crust below Barbados, as proposed by Hess (1938).

Barbados and Trinidad sedimentary conditions show some remarkable similarities, and the recorded velocity data from the Barbados profile is similar to that observed over the Trinidad shelf. The velocities of 2.75 km/sec and 3.37 km/sec may therefore be matched with the corresponding data recorded in South and Central Trinidad.

ACKNOWLEDGMENTS

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The four well surveys reported herein were shot by Seismograph Service Ltd., London.

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DISCUSSIONS AND COMMUNICATIONS

EXACT TRUE DIP FOR A SINGLE CONSTANT-VELOCITY REFLECTOR*

CALVIN KIRBY†

Methods of determining the true dip, or velocity, or both when the velocity is constant are described in the literature. When the sines of the angles of dip are known for two spreads in line with the shotpoint, and at right angles, the true dip can be found exactly (Nettleton, 1940; p. 294–295; and others). An exact extension of this result to two spreads not at right angles is simple, although apparently the equations have not been published. A slightly more general case in which at least two detectors are assumed to be in line with the shotpoint can also be solved exactly by elementary means. The general case in which no two detectors are in line with the shotpoint has apparently not been published. For the special cases mentioned, the present treatment is of greater generality, since the detectors here are not required to be in a level plane, which seems to be a requirement of previous methods. The present work is general in part through being three-dimensional and including the dip. The wave front is not assumed to be planar.

The problem of finding true dip is really that of fixing the position of a plane in space. A simple description of a plane in space is by means of the vector normal to the plane or three scalars. If the velocity is assumed to be known, the unknown vector perpendicular may be related to the reflection times to three detectors. This is a general solution, for the problem cannot be solved with less information, and more is unnecessary. If the velocity is assumed to be constant and unknown, it may be determined by adding a fourth detector; further remarks on this subject will be found in the latter part of the article.

In Figure 1, Q' is the image of the shotpoint Q, a point source, in the plane reflecting bed DEF; hence QQ' is perpendicular to the reflector. The configuration of the surface is assumed to be known, i.e., all angles and distances are known, and the three detectors A, B, and C, are regarded as non-collinear. The reflections to A, B, and C, impinge on the reflector at the points D, E, and F. The planes QDA, QEB, and QFC, are perpendicular to the reflector. It will also be convenient to think of BA and BC as cable spreads. The point Q, it should be mentioned, is not necessarily in the plane of the detectors.

The product of the reflection time by the (constant) velocity will be desig-

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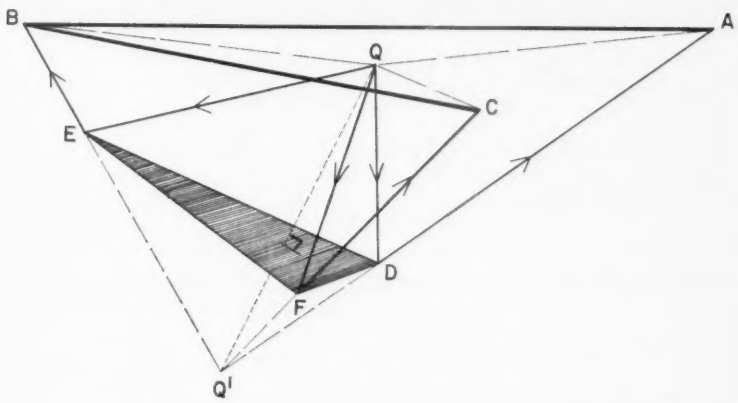

FIG. 1. The shotpoint Q generally is not in the plane of the three detectors A, B, and C. The plane of the reflector is defined by D, E, and F. QQ' is perpendicular to the reflector.

nated by the letter τ; hence, the magnitudes of the vectors are related by

$$\begin{aligned} QD + DA &= \tau_A = Q'A, \\ QB + EB &= \tau_B = Q'B, \\ QF + FC &= \tau_C = Q'C. \end{aligned} \tag{1}$$

It is also evident, remembering the law of reflection, that

$$\begin{aligned} QD &= Q'D, \\ QE &= Q'E, \\ QF &= Q'F. \end{aligned} \tag{2}$$

From the diagram, it is easy to see that

$$\begin{aligned} \overline{QD} + \overline{DA} &= \overline{QA}, \\ \overline{QE} + \overline{EB} &= \overline{QB}, \\ \overline{QF} + \overline{FC} &= \overline{QC}. \end{aligned} \tag{3}$$

and

$$\begin{aligned} \overline{Q'Q} &= \overline{Q'A} - \overline{QA} = \overline{Q'B} - \overline{QB} = \overline{Q'C} - \overline{QC} \\ &= \overline{Q'D} - \overline{QD} = \overline{Q'E} - \overline{QE} = \overline{Q'F} - \overline{QF}. \end{aligned} \tag{4}$$

The vectors $\overline{Q'D}$, $\overline{DA}$, and $\overline{Q'A}$, for example, are collinear, so that

$$\begin{aligned}
\overline{Q'A} &= \left(\frac{\tau_A}{QD}\right)\overline{Q'D} = \left(\frac{\tau_A}{\tau_A - QD}\right)\overline{DA}, \\
\overline{Q'B} &= \left(\frac{\tau_B}{QE}\right)\overline{Q'E} = \left(\frac{\tau_B}{\tau_B - QE}\right)\overline{EB}, \\
\overline{Q'C} &= \left(\frac{\tau_C}{QF}\right)\overline{Q'F} = \left(\frac{\tau_C}{\tau_C - QF}\right)\overline{FC}.
\end{aligned} \tag{5}$$

The vector $\overline{R}$, which is perpendicular to the plane of the detectors, is defined by

$$\overline{R} = (\overline{QA} - \overline{QB}) \times (\overline{QC} - \overline{QB}) = \overline{BA} \times \overline{BC}.$$

The vectors $\overline{Q'A}$, $\overline{Q'B}$, and $\overline{Q'C}$, can be expressed in terms of three known non-coplanar vectors, or

$$\begin{aligned}
\overline{Q'A} &= a_1\overline{R} + a_2\overline{BA} + a_3\overline{BC}, \\
\overline{Q'B} &= b_1\overline{R} + b_2\overline{BA} + b_3\overline{BC}, \\
\overline{Q'C} &= c_1\overline{R} + c_2\overline{BA} + c_3\overline{BC}.
\end{aligned} \tag{7}$$

But by (4), since for example $\overline{Q'C} = \overline{Q'A} - (\overline{QA} - \overline{QB}) + (\overline{QC} - \overline{QB})$,

$$\begin{aligned}
b_1 &= a_1 & c_1 &= a_1 \\
b_2 &= a_2 - 1 & c_2 &= a_2 - 1 \\
b_3 &= a_3 & c_3 &= a_3 + 1.
\end{aligned}$$

When these values are used in (7), the system may be solved for the coefficients a_1, a_2, and a_3, by forming the scalar products of each side of the equations with themselves (i.e., by "squaring" each equation) and subtracting one of them from the other two.

If the following substitutions are made,

$$\begin{aligned}
\tau_{AB} &= \tau_A^2 - \tau_B^2, \\
\tau_{BC} &= \tau_B^2 - \tau_C^2, \\
\mu_0 &= \tfrac{1}{2}[(BA)^2(BC)^2 - (\overline{BA} \cdot \overline{BC})^2]^{-1}, \\
\mu_1 &= (BC)^2\mu_0, \\
\mu_2 &= \overline{BA} \cdot \overline{BC}\mu_0, \\
\mu_3 &= [(BA)^2(BC)^2 + (BC)^2\overline{BA} \cdot \overline{BC} - 2(\overline{BA} \cdot \overline{BC})^2]\mu_0, \\
\mu_4 &= (BA)^2\mu_0, \\
\mu_5 &= (BA)^2(\mu_2 - \mu_1),
\end{aligned}$$

then the coefficients become

$$\begin{aligned} a_2 &= \mu_1\tau_{AB} + \mu_2\tau_{BC} + \mu_3, \\ a_3 &= -\mu_2\tau_{AB} - \mu_4\tau_{BC} + \mu_5, \end{aligned} \tag{8}$$

and

$$a_1 = \pm R^{-1}[\tau_A{}^2 - a_2{}^2(BA)^2 - a_3{}^2(BC)^2 - 2a_2a_3\overline{BA}\cdot\overline{BC}]^{1/2}.$$

Because the coefficients a_1, a_2, and a_3, are now known, the vectors $\overline{Q'A}$, $\overline{Q'B}$, and $\overline{Q'C}$, are also known. The vector magnitudes QD, QE, and QF, may be found from (3) and (5), where, for example,

$$\begin{aligned} \overline{QD} &= \overline{Q'D} + \overline{QA} - \overline{Q'A}, \\ &= \overline{QA} + \left(\frac{QD - \tau_A}{\tau_A}\right)\overline{Q'A}. \end{aligned}$$

This expression may be "squared" and solved for QD. In a similar manner, it is possible to find QE and QF. Thus, the vectors $\overline{Q'D}$, $\overline{Q'E}$, $\overline{Q'F}$, $\overline{DA}$, $\overline{EB}$, and $\overline{FC}$, are given by (5), and the vectors $\overline{QD}$, $\overline{QE}$, and $\overline{QF}$, can be found from (3) or (4).

The most important vector, $\overline{Q'Q}$ or $\overline{QQ'}$, is obtainable from (4). One half the magnitude of this vector gives the distance to the reflector.

In general Q does not lie in the plane of the detectors nor is the plane of the detectors level, and it becomes necessary to introduce another co-ordinate system. If the right-handed mutually orthogonal unit vectors $\bar{\imath}$, $\bar{\jmath}$, and $\bar{k}$, are oriented with the $\bar{\imath}$-axis directed to the nadir and the $\bar{\jmath}$-axis to the north, the maximum dip of the reflector is

$$\cos\theta = \frac{\bar{\imath}\cdot\overline{QQ'}}{QQ'}. \tag{9}$$

If

$$\bar{l} = \frac{\bar{\imath}\times(\bar{\imath}\times\overline{QQ'})}{(QQ')\sin\theta}$$

is the unit vector lying in the plane of $\bar{\jmath}$ and $\bar{k}$ and pointing in the down-dip direction of the reflector, the azimuth α of $\bar{l}$ measured clockwise from the north is defined by

$$\sin\alpha = \bar{l}\cdot\bar{k} = -\frac{\overline{QQ'}\cdot\bar{k}}{(QQ')\sin\theta}$$

and

$$\cos \alpha - \bar{l} \cdot \bar{j} = - \frac{\overline{QQ'} \cdot \bar{j}}{(QQ') \sin \theta} . \tag{10}$$

The preceding equations constitute necessary mathematical conditions for a solution. A valid physical solution requires that the product of the velocity and the reflection time to a detector equals or exceeds the distance from the shotpoint to the detector.

DETERMINATION OF VELOCITY

By adding a fourth detector with position vector G, the velocity may be found if it is assumed to be constant. For generality, G is regarded as not lying in the plane formed by the three detectors A, B, and C, although G can be collinear with any two of them.

Since any set of three detectors must determine $\overline{Q'Q}$, the vector $\overline{Q'G}$ by (4) can be written as

$$\overline{Q'G} = \overline{Q'A} - \overline{QA} + \overline{QG} = \overline{Q'A} + \overline{AG}.$$

The relations between the components following (7) may be written, with the preceding equation, as

$$\begin{aligned} \overline{Q'A} &= \overline{Q'A}, \\ \overline{Q'B} &= \overline{Q'A} + \overline{AB}, \\ \overline{Q'C} &= \overline{Q'A} + \overline{AC}, \\ \overline{Q'G} &= \overline{Q'A} + \overline{AG}. \end{aligned} \tag{11}$$

The magnitudes of the vectors on the left of (11) are equal to the product of the velocity by the corresponding reflection time. Four unknown scalars occur in (11), the velocity V and the coefficients a_1, a_2, and a_3, which may be found by squaring each equation of (11). If the quantity $(Q'A)^2$ occurring on the right-hand side in the second, third, and fourth, equations of (11) after squaring is set equal to $V^2T_A^2$ and moved to the left side, the second and third of (11) involve only a_2 and a_3, and these coefficients may be found in terms of V. By substituting a_2 and a_3 in the fourth of (11), a_1 may also be expressed in terms of V. The velocity may be found by substituting the expressions a_1, a_2, and a_3, into the right-hand side of the first of (11) or (7). Generally,

$$V^2 = \frac{(Q'A)^2}{T_A^2} = \frac{(Q'B)^2}{T_B^2} = \frac{(Q'C)^2}{T_C^2} = \frac{(Q'G)^2}{T_G^2} . \tag{12}$$

With the coefficients and velocity known, the problem is reduced to that of three detectors.

The number of independent measurements of the generalized true dip at one shot point for a planar reflector is given by the number of combinations of n detectors taken four at a time. The theory of statistics shows that it is seldom worthwhile to use more than about 10 measurements of a quantity by a given experimental method. Six detectors, suitably spaced, provide fifteen combinations. Rather than use a large number of combinations of detectors for a precision which only increases with the square root of the number of combinations, it would be more profitable to improve the precision of a single determination. The application of weathering corrections will increase precision, and it is likely that a better understanding of the nature of a reflection will serve to improve both accuracy and precision.

The reflecting horizon was explicitly assumed to be planar. This assumption is not necessary, and in certain instances it would be well to have other solutions available, and this can be done by using more than four detectors. While data may be "smoothed" by adding more detectors, the form of a (warped) reflector cannot be known exactly even by adding an infinite number of detectors unless the velocity is known exactly.

REFERENCE

Nettleton, L. L., 1940, Geophysical prospecting for oil: New York, McGraw-Hill Book Company, Inc.

TECHNICAL NOTES

DIFFICULTIES IN SCANNING CURRENT GEOPHYSICAL LITERATURE

We have read with great interest Mr. Hutchison's paper entitled "Magnetic Analysis by Logarithmic Curves" (GEOPHYSICS, v. 23, p. 749–769) concerning a problem treated by ourselves at the 12th Congress of the European Association of Exploration Geophysicists at Brussels in June, 1957.

Our paper, "Sur l'interprétation des anomalies gravimétriques et magnétiques," was published in the December, 1957, issue of *Geophysical Prospecting*. The two methods are based on the same principle, but their procedure of application is often different; furthermore, our paper deals also with some practical examples. Therefore, we believe that it would be of some interest to indicate it to your readers, especially since, though earlier published, it was not mentioned by Mr. Hutchison.

We appreciated your co-operation when one of the two signers wrote to you to draw our attention to our EAEG communication about electrical soundings over dippling beds, which was not mentioned in a general report about this problem, published in GEOPHYSICS. At that time, you suggested that we prepare a paper which was subsequently published in GEOPHYSICS (v. 21, p. 780–793). Nevertheless, these two cases show that European researches are not generally known to American geophysicists, and we believe that this is of no advantage to anyone.

In this connection, we notice that Mr. Hutchison attributes the first use of bi-logarithmic co-ordinates in electrical sounding interpretation to Dr. Roman (1934). To the best of our knowledge, it was Mr. H. G. Doll, presently Chairman of the Board of the Schlumberger Well Surveying Corporation, who was the first to use them in 1930. The master curves which have been, and still are, in use at the Compagnie Générale de Géophysique for over 25 years and have been reproduced in a special issue of *Geophysical Prospecting* (v. 3, suppl. no. 3, September, 1955), are, mostly, from 1933.

There is also a paper prior to Mr. Hutchison's and ours which we did not know when our own paper was published. It deals with part of the same subject, and its title is, approximately, "Logarithmic Master Curves in Gravity Interpretation"; the author is Mr. A. A. Nepomniachik; and the paper appeared in *Izvestia Acad. Nauk. SSSR.*, Geoph. Ser., 1952, no. 1, p. 40–46.

We hope that all this may be of some use to our fellow geophysicists.

JÉRÔME CHASTENET DE GERY
HENRI NAUDY
Compagnie Générale de Géophysique
Paris, France

Received by the Editor February 10, 1959.

REPLY TO THE COMMENTS BY J. CHASTENET DE GERY AND H. NAUDY

In the introduction to my paper, I mentioned an apparent lack of "sound, complete, and directly analytical" methods. It is encouraging to learn that such a method appeared in print at about the time I wrote those words, and also that a Russian paper, apparently on the same general subject (I have not yet seen it) had appeared five years earlier.

Now, Mr. Editor, I think that GEOPHYSICS has occasionally republished worthy papers from other journals; and this paper by Messrs. Chastenet de Gery and Naudy strikes me as one that would be interesting to North American Geophysicists. I hope you decide to use it; but if you do, please don't repeat the mistake made by *Geophysical Prospecting* in translating "compartiment cylindrique" into "cylindrical compartment." It is misleading. At first I was quite confused by their Figure 2, believing that it was meant to represent a vertical cylinder and wondering why my own curves for that case were so very different. Then it became clear that "cylindrique" must signify uniformity along strike—a two-dimensional case—and that the curves of Figure 2 are simply the dyke functions of even symmetry—called ϕ in my paper. Similar confusion could arise from their Figure 5, which illustrates a specific form, more or less related to my "thin bed" class.

There is a further point that might be clarified if this paper is to be republished. The gravity cases all deal with vertical gradient, but there seems to be no statement as to whether the gradient is directly measured or merely computed from observed gravity. I mention this because from logarithmic master curves for the *gravity* anomaly of the general dyke, I can see no satisfactory way of resolving the "radius" of anomaly into its two components of depth and breadth; the difference between a broad near-surface dyke and a thin deeper dyke is hardly readable. And so, depth determinations from gravity must be even less certain than depth determinations from magnetics (I have given a sample of the latter at the top of p. 766 in my paper). It may be possible to do better with a gravity gradient directly observed. This would be a very interesting point. But it is not logical to suppose that a computed gradient can give more information than the observations it is based on.

I must apologize if I have misplaced the credit for logarithmic ploting in geophysical analysis. I wasn't certain, but I thought it might be a toss-up between Roman and Stefanesco, as these two seemed to be the most significant contributors among the many who published methods of resistivity analysis shortly after Hummel's fundamental paper of 1929. The resistivity papers I cited give numerous other references to European and North American authors.

RALPH D. HUTCHISON
Toronto, Canada

EDITOR'S NOTE: For a step toward an improvement in this situation, the

Reviews Section, beginning with this issue (see p. 627), will carry the abstracts of the papers in *Geophysical Prospecting*.

GEOPHYSICS does not intentionally republish technical articles from other journals. Accordingly we cannot conform to Mr. Hutchison's suggestion.

Geophysical Prospecting is a magazine that could be read with profit by all geophysicists. SEG members are privileged to obtain membership in EAEG and thus receive *Geophysical Prospecting* without the necessity of obtaining sponsors. Application forms are available at the SEG Business Office.

AMMONIUM NITRATE BLASTING AGENTS

I have read with interest the article by Jack Martin and Thomas O. Hall on ammonium nitrate blasting agents in seismic work (GEOPHYSICS, v. 24, p. 155–163).

As you may know, there are several controversial aspects to this subject which have not as yet been settled. We have an extensive research program under way on the explosibility of AN for blasting purposes and have held two symposia on the subject at the Missouri School of Mines. The proceedings of the first* is being forwarded to you and the second will be mailed when it comes off the press shortly. There is a review of the latter in the January, 1959, issue of the *Engineering and Mining Journal*. The papers deal with AN-fuel-oil explosives, slurries, and other types of AN explosives. Slurries of AN-TNT are receiving considerable attention for use in wet holes and have been found to be an effective and powerful source of explosive energy.

In a paper presented at the AIME meeting in San Francisco concerning the shooting of AN-fuel mixes in sprung holes at the Utah Copper Company, it was reported that this could be done with safety if certain precautions were observed. Reprints may be obtained from the AIME headquarters in New York City.

I would also refer you to a recently published book by M. A. Cook, entitled *The Science of Explosives*, which has an excellent section on AN explosives.

There is considerable doubt concerning the so-called "overdrive" principle. Explosives may be driven beyond thier characteristic velocity by a higher velocity explosive primer, but only for a few charge diameters. If AN and fuel oil are thoroughly mixed, the mixture may be detonated unconfined on the ground by a No. 6 blasting cap. Its sensitivity is dependent upon a large number of variables including loading density, prill density, percent oil, inert coating, primer geometry, and other factors.

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Received by the Editor February 27, 1959.

* Third Annual Symposium on Mining Research, Technical Series No. 95, 1958, Missouri School of Mines, Rolla, Missouri.

DEPARTMENTS

PATENTS

O. F. RITZMANN†

ELECTRICAL PROSPECTING

U. S. No. 2,863,546. E. L. Josefowicz. Iss. 12/9/58. App. 3/19/56. Assign. The Best Foods, Inc.

Magnetic Flux Monitoring Apparatus. A device for controlling the feed of metal caps to a bottle-capping machine in which the caps pass through the interior of a mutual inductance whose coils are in a balanced circuit whose unbalance controls a relay that regulates the feed.

U. S. No. 2,869,071. G. L. Esterson. Iss. 1/13/59. App. 10/29/56.

Apparatus for Measuring Electrical Conductivity of Fluids. An inductive conductivity measuring apparatus having two toroidal coils along whose axis the fluid flows, one coil being excited by a-c power and the other coil having a reference winding connected to one phase of a two-phase indicator and a pick-up winding connected through an amplifier to the other phase of the indicator.

U. S. No. 2,869,074. C. W. Clapp. Iss. 1/13/59. App. 10/26/53. Assign. General Electric Co.

Single-Turn Coil for Metal Detector. A tramp-metal detector having two single-turn coils through which a conveyor belt passes, the coils being connected in a balanced circuit excited by an oscillator and a phase discriminator used to detect unbalance.

U. S. No. 2,870,427. W. E. Frank and F. F. Ohntrup. Iss. 1/20/59. App. 3/11/52. Assign. W. K. Kellogg Foundation.

Device for Detecting and Indicating Proximity of Objects. A blind man's staff having a fixed frequency oscillator and a second oscillator whose frequency depends on the loading of an antenna on the side of the staff with the beat note fed to an earphone, and also having an oscillator with an antenna coil at the bottom of the staff to detect an object on the ground by a change in its mode of oscillation.

U. S. No. 2,872,638. S. B. Jones. Iss. 2/3/59. App. 3/31/55. Assign. California Research Corp.

Ocean Bottom Stratigraphy Survey. An electrical ocean bottom exploring system in which a heavy flat electrode assembly is dragged along the water bottom, the electrode assembly having on its lower surface a central current electrode surrounded by an array of annular electrodes.

U. S. No. 2,874,348. A. A. Brant and A. W. Love. Iss. 2/17/59. App. 10/4/54. Assign. Newmont Mining Corp.

Electromagnetic Method of Geophysical Exploration. An electromagnetic system for determining the presence of a conducting ore body from a nearby drill hole having a primary coil at the top of the hole excited by low frequency a-c and a movable exploring coil in the drill hole and measuring the phase angle between the picked-up signal and the primary a-c for various depths of the pick-up coil.

U. S. No. 2,874,349. H. N. Staats. Iss. 2/17/59. App. 6/2/55.

Apparatus for Detecting and Measuring the Depth of Reinforcing Rods. An oscillator and small exploring coil for locating conducting material embedded in non-conducting material, and which is calibrated by placing the coil on a block of wood with an inclined grove in which is placed a sample of reinforcing rod so that the indication at known depth can be observed.

† Gulf Oil Corporation, Patent Department.

GEOCHEMICAL PROSPECTING

U. S. No. 2,871,105. P. J. Moore. Iss. 1/27/59. App. 3/12/52. Assign. National Lead Co.

Hydrocarbon Detection. A vessel for detecting hydrocarbons in well cuttings having at the bottom a high-speed disintegrating blade and at the top a gas-detecting filament surrounded by a baffle that permits gas to reach the filament but stops water particles.

U. S. No. 2,875,135. J. Maddox, Jr. Iss. 2/24/59. App. 12/28/56. Assign. The Texas Co.

Geomicrobiological Prospecting. A method of testing soil samples for hydrocarbon consuming bacteria by mixing the soil sample with a nutrient salt and a hydrocarbon gas under quiescent conditions and subsequently incubating the mixture under agitation.

RADIOACTIVITY PROSPECTING

U. S. No. 2,868,990. W. A. Reardon, D. H. Lennox, and R. G. Nobles. Iss. 1/13/59. App. 12/12/55. Assign. U. S. A.

Neutron Source. A neutron source having a beryllium block with a cylindrical recess containing a cylinder of antimony 124 in a fluid-tight aluminum casing with the recess in the block closed by a beryllium plug.

U. S. No. 2,871,365. G. M. Cahen, P. Bonnet and P. Treille. Iss. 1/27/59. App. 5/7/54 and 4/29/55. Assign. Etat Francais.

Apparatus for Detecting Radioactivity. A radioactivity detector having an ionization chamber in series with a load resistor and a condenser which may be connected to a charging circuit and an electrometer connected across the resistor and a reference condenser that is connected to the same charging circuit.

U. S. No. 2,871,366. F. A. Hill. Iss. 1/27/59. App. 12/29/55. Assign. Librascope, Inc.

Apparatus for Sensing Radioactivity. A radioactivity detector having two ionization chambers and a collector that is biased so as to collect particles of the same polarity from the two chambers when exposed to low intensity radiation and to collect particles of opposite polarity at high intensity.

U. S. No. 2,871,367. L. S. Gournay. Iss. 1/27/59. App. 8/1/55. Assign. Socony Mobil Oil Co., Inc.

Gamma Ray Collimating Device. A device for collimating gamma rays from an extended source to permit examination of various parts of the source and having an air-filled slit leading to a gamma-ray detector with the slit and detector surrounded with mercury.

U. S. No. 2,873,399. A. D. Garrison. Iss. 2/10/59. App. 5/27/54. Assign. Texaco Development Corp.

Radiation Detector. A radioactivity detector whose cathode is in the form of flat plates having juxtaposed projecting ridges to form elongated openings of square cross section along the axis of which the anode wires extend.

U. S. No. 2,874,304. R. M. Lichtenstein. Iss. 2/17/59. App. 3/31/55. Assign. General Electric Co.

Ionization Chamber. A radioactivity detector having a heated electron-emitting cathode surrounded by a cylindrical anode and containing a gas with a high electron-mobility coefficient and a trace of a gas having large molecules.

U. S. No. 2,874,305. H. N. Wilson and F. M. Glass. Iss. 2/17/59. App. 10/17/55. Assign. U.S.A.

Radiation Integrator. A radioactivity detector having an ionization chamber with one electrode directly connected to the grid of an electrometer tube that feeds a trigger circuit driving a counter.

U. S. No. 2,875,364. G. Herzog. Iss. 2/24/59. App. 12/31/53. Assign. The Texas Co.

Radiation Detector. A device for measuring total gamma radiation and having hinged semicylindri-

cal shells that can enclose a person, each shell having along its elements a series of gamma-ray detectors with aligned perforated horizontal cathode plates and a long anode wire passing through the openings in the plates.

SEISMIC PROSPECTING

U. S. No. 2,862,414. L. P. Stephenson. Iss. 12/2/58. App. 7/27/55. Assign. California Research Corp.

Optical Method for Eliminating False Strata from a Seismic Profile Sheet. A system of setting up a pair of mirrors on a seismic profile and observing multiple reflections in the mirrors to predict and dentify the positions of multiple reflections on the profile.

U. S. No. 2,864,072. F. G. Blake. Iss. 12/9/58. App. 6/16/54. Assign. California Research Corp.

Method and Apparatus for Eliminating Phase Distortion in Seismic Signals. A seismic recording system in which the detector signal is filtered and recorded on an endless belt and played back in reverse time through a similar filter and recorded a second time, the second recording being played back in reverse to recover the phase-corrected seismogram for further processing.

U. S. No. 2,864,073. W. T. Harris. Iss. 12/9/58. App. 9/7/55. Assign. The Harris Transducer Corp.

Demountable Cable Hydrophone. An annular magnetostrictive or piezoelectric transducer that may be slipped over a marine seismic cable and held in position by clamps at each end of the transducer case.

U. S. No. 2,864,167. J. A. Hall, Jr. Iss. 12/16/58. App. 1/20/55.

System and Apparatus for Analysis of Seismographic Records. A device for plotting reflections picked on a seismic record having a scanning head that moves along the record with an indicator whose shape is automatically changed in accordance with changing step-out and which can be angularly adjusted to fit picked reflections, a plotting head being mechanically connected to the indicator to give the reflecting surface in proper attitude for plotting on a section.

U. S. No. 2,865,290. G. B. Bonsper. Iss. 12/23/58. App. 2/7/55. Assign. American Cyanamid Co.

Cartridge Coupling Device. A dynamite cartridge coupling sleeve having in its wall a number of prongs with inwardly projecting spurs, the spur being forced in to engage the cartridge when an outer sleeve is forced over the coupling sleeve.

U. S. No. 2,866,512. L. R. Padberg, Jr. Iss. 12/30/58. App. 7/3/53.

Method of Subsurface Exploration by Sonic Means. A sonic pulse system of seismic prospecting in which audio-frequency pulses of less than 10 milliseconds duration and of energy comparable with that of an explosion are projected as a beam into the earth and the travel time of reflections measured.

U. S. No. 2,867,490. T. Bardeen. Iss. 1/6/59. App. 9/29/55. Assign. Gulf Research & Development Co.

Sequence Indicator for Oscillograms. A system for identifying successive multichannel seismograph records by connecting an oscillator to one of the recording channels through a stepping switch so that the oscillator signal appears on successive traces in known sequence.

U. S. No. 2,867,775. G. M. Groenendyke. Iss. 1/6/59. App. 11/25/53. Assign. Socony Mobil Oil Co., Inc.

Time Variable Filter. An automatic filter control for a seismograph amplifier having a first filter with a predetermined amplitude-frequency curve and paralleled by a second filter having a variable phase-amplitude characteristic and delivering an inverted signal, and a time control on the phase-amplitude control of the second filter.

U. S. No. 2,867,779. T. Bardeen and I. C. Zacher. Iss. 1/6/59. App. 11/14/55. Assign. Gulf Research & Development Co.

Seismograph Filter Systems. A band-pass filter circuit having high-pass and low-pass sections in cascade and using saturable core inductances, the circuit also containing resistors that are adjusted so that the high and low cut-offs can be electrically adjusted by a common control of the saturation current in the inductances.

U. S. No. 2,867,788. W. R. Harry. Iss. 1/6/59. App. 2/27/43. Assign. Bell Telephone Laboratories, Inc.

Object Locating Systems. A sonic echo-ranging system having an omnidirectional pulse source and a directional hydrophone connected to a resolving circuit and c-r display tube, and using two amplifiers in each channel with the gain of one amplifier varying inversely to the variation of reflection intensity with distance and the gain of the other amplifier varying proportional to time subsequent to energization of the source.

U. S. No. 2,869,226. G. A. Schurman. Iss. 1/20/59. App. 3/24/54. Assign. California Research Corp.

Cable Assembly Method and Apparatus. A method of assembling pressure detectors and electrical cables into a rubber sleeve to make up a marine seismic cable by making up the assembly in a larger pipe to the end of which the sleeve is attached and blowing the assembly into the sleeve with compressed air.

U. S. No. 2,869,851. H. B. Sedgfield, M. L. Jofeh, and R. Albrecht. Iss. 1/20/59. App. 3/28/49 and 3/22/50. Assign. The Sperry Gyroscope Co. Ltd.

Apparatus Adapted to Measure Accelerations and Inclinations. An accelerometer having a suspended coil also carrying a condenser-type displacement detector connected to a detecting circuit and d-c amplifier that supplies current to the coil to counteract the displacing force.

U. S. No. 2,869,966. J. M. Cunningham. Iss. 1/20/59. App. 6/6/52, 8/3/55 and 9/17/57. Assign. Techno Instrument Co.

Recording Sheet and Means for Mounting Same on a Rotary Drum. A clamp for holding on a drum a recording sheet perforated at both ends with the perforations overlapping, the clamp having fingers that go through both perforations and apply tension to the sheet.

U. S. No. 2,870,422. P. Gindes and J. S. Linn. Iss. 1/20/59. App. 2/25/57. Assign. Genisco, Inc.

Accelerometer. A suspended armature reluctance type accelerometer having two sets of inwardly-projecting radial pole pieces that are angularly displaced about the axis of sensitivity of the device and wound with pick-up coils, axial movement of the armature increasing the reluctance of one magnetic circuit and decreasing the reluctance of the other.

U. S. No. 2,870,708. G. M. Pavey, Jr. Iss. 1/27/59. App. 8/19/55. Assign. Marine Instrument Co.

Firing Line for Subaqueous Geophysical Prospecting. A firing line for marine seismic operations having a two-conductor insulated cable with one conductor connected to an annular electrode at the outboard end of the line and the other conductor connected to an exposed bare wire, the charge being electrically and mechanically connected to a metal ring that is slipped over the firing line at the boat and that contacts the annular electrode when the charge reaches the end of the line, the firing circuit being completed through the sea water.

U. S. No. 2,871,089. G. B. Loper and R. R. Pittman. Iss. 1/27/59. App. 11/28/52. Assign. Socony Mobil Oil Co., Inc.

Recording Camera for Monitoring Seismic Waves. A galvanometer type recorder for monitoring

magnetic recordings and using two lens systems that successively traverse the film of a self-developing type of camera.

U. S. No. 2,871,459. T. M. Berry. Iss. 1/27/59. App. 5/6/46. Assign. General Electric Co.

Submerged Object Locating. An echo-locating system in which a predetermined number of short pulses of successively different frequences are transmitted and the receiver is controlled so as to make it insensitive to the particular frequency being transmitted.

U. S. No. 2,871,461. B. D. Lee. Iss. 1/27/59. App. 11/20/53. Assign. The Texas Co.

Seismic Prospecting. A mixing circuit in which the signals from two geophones are each split into two phases which are respectively multiplied and recombined in a push-pull output circuit.

U. S. No. 2,871,665. H. Brandt. Iss 2/3/59. App. 10/20/55. Assign California Research Corp.

Seismic Cable Lifting Apparatus. A system for controlling the buoyancy of a geophone cable in marine seismic operations in which the cable is fastened to an auxiliary cable that has air pockets and through which liquid can be forced to compress the air in the pockets when it is desired to reduce the buoyancy.

U. S. No. 2,871,785. A. J. Hintze and M. C. Klaus. Iss. 2/3/59. App. 9/4/53. Assign. Phillips Petroleum Co.

Shot Hole Protective Device. A shot deflector and shot-hole casing anchor having a frame on the casing head and a conical truck-mounted hood that can be set on the frame, the hood having a curved stack to deflect debris coming out of the shot hole.

U. S. No. 2,871,970. R. E. Doe, R. E. Daniel, and G. C. Alvey. Iss. 2/3/59. App. 3/18/54. Assign. California Research Corp.

Method and Apparatus for Amplifying Seismic Signals. A seismograph volume-control system having an automatic gain control that is cut on and off by a timer whose sequence is initiated by the shot moment impulse so that some parts of the record have avc and some do not.

U. S. No. 2,872,995. A Wolf. Iss. 2/10/59. App. 5/13/57. Assign. Geophysical Research Corp.

Seismic Reflection Prospecting Technique. A reflection recording system in which two vertically spaced geophones are buried below the shot point and their output signals linearly added, and also the difference of their output signals integrated, the additive signal and the integrated difference signal being combined to cancel direct waves from the shot.

U. S. No. 2,872,996. R. J. Runge. Iss. 2/10/59. App 10/17/57. Assign. Pan American Petroleum Corp.

Seismic Wavelet Contraction. A system for improving the resolution of seismic wavelets in a complex wave and in which the wave is successively reproduced through a channel having an attenuator, a differentiator, and a flat-frequency-response amplifier and rerecorded, with every other reproduction being reversed in time, and with the adjustment of the attenuator varied with the number of the reproduction in accordance with the coefficients of a series representing an exponential expansion, and the successive reproductions added to the orignal wave.

U. S. No. 2,873,103. R. F. Hautly. Iss. 2/10/59. App. 10/7/53. Assign W. F. Sprengnether Instrument Co., Inc.

Seismological Instruments. An earthquake accelerometer having a vertical suspension carrying a mirror on a nonmagnetic cylinder that surrounds the suspension and has an eccentric bar on one side of the cylinder, the entire system being between the poles of a permanent magnet to damp rotation of the cylinder.

U. S. No. 2,874,356. G. Peterson. Iss. 2/17/59. App. 6/28/48, 4/2/52 and 1/25/55. Assign. Phillips Petroleum Co.

Method of and Apparatus for Seismic Prospecting. A multichannel radio geophone system in which the geophone signals are heterodyned against a single local oscillator and using a coupling circuit that provides separation of signals from the separate geophones.

U. S. No. 2,874,795. W. E. N. Doty and M. R. Lee. Iss. 2/24/59. App. 10/20/54. Assign. Continental Oil Co.

Method and Apparatus for Determining the Travel Times of a Signal Propagated Over a Plurality of Paths. A varying-frequency continuous-wave seismic prospecting system using a correlation analysis of the recorded wave and in which the source is moved during the transmission interval.

U. S. No. 2,875,017. V. T. Reynolds. Iss. 2/24/59. App. 11/25/53. Assign. Southwestern Industrial Electronics Co.

Vibration Recording Device. A seismograph recording system in which the oscillograph beams pass through slits which cut off the beam at a preselected amplitude, each beam having a cylindrical lens that focusses excursions of the beam at a point so that the resulting trace is a straight line with gaps representing high amplitudes.

U. S. No. 2,875,352. A. W. Orlacchio. Iss. 2/24/59. App. 3/4/53. Assign. Gulton Industries, Inc.

Blast Gauge. A piezoelectric blast pressure gauge having a pair of barium titanate crystals in a disk-shaped housing whose periphery is tapered to a sharp edge and which is oriented so that the edge faces the blast point.

(See also Patents 2,867,170 and 2,874,602 listed under Miscellaneous.)

WELL LOGGING

U. S. No. 2,864,173. J. H. Castel. Iss. 12/16/58. App. 3/8/55. Assign. Perforating Guns Atlas Corp.

Electrical Well Caliper Tool. A well caliper having a pair of caliper arms that are geared to a potentiometer so that one arm moves the case and the other arm moves the slider of the potentiometer whose resistance is indicated at the surface.

U. S. No. 2,865,463. O. A. Itria. Iss. 12/23/58. App. 1/19/56. Assign. The Texas Co.

Determination of Propagation Characteristics of Earth Formations. A velocity survey cable and detector assembly in which each detector is bridged by a flexible strain member so that the bridged detector is free of tension and thereby isolated from cable-borne vibrations.

U. S. No. 2,866,155. P. W. Martin. Iss. 12/23/58. App. 3/4/55.

Apparatus for Visually Inspecting Oil Well Casings. A pipe testing device having a small exploring magnet that is rotated inside the pipe to magnetically scan a circumferential strip and with the magnet coil connected at the surface to a c-r tube with synchronized sweep so as to visually indicate magnetic irregularities picked up by the magnet.

U. S. No. 2,867,728. H. C. Pollock. Iss. 1/6/59. App. 10/28/54. Assign. General Electric Co.

Logging Apparatus. A radioactivity logging system using a pulsed neutron source having an ion source and an accelerator with the ion source controlled by a timing signal, and a detector that indicates the effect of the neutrons on the surrounding material.

U. S. No. 2,868,012. M. P. Lebourg. Iss. 1/13/59. App. 11/16/54. Assign. Schlumberger Well Surveying Corp.

Flowmeter. A subsurface flow meter having a single-bladed paddle that is rotated in the fluid on

an axis transverse to the borehole by an electric motor whose power variation is recorded, a point of phase reference in the sinusoidal power curve being provided by a point of close clearance in the path of the paddle.

U. S. No. 2,868,311. F. N. Tullos. Iss. 1/13/59. App. 3/7/57. Assign. Jersey Production Research Co.

Acoustic Impedance Logging. An acoustic impedance logging apparatus having a series of cylindrical transmitters alternating with cylindrical receivers that are connected in series and spaced so that at the frequency of operation the longitudinal waves from the transmitters cancel and only radial waves are effective.

U. S. No. 2,868,506. A. C. Nestle. Iss. 1/13/59. App. 6/1/54. Assign. The Texas Co.

Determination of Fluid Movement in Bore Holes. A method of locating zones of lost circulation by injecting a radioactive tracer into the mud stream as it leaves the drill bit and detecting radioactivity in the mud at a point above the bit, so that loss of mud to the formation at the bit can be detected.

U. S. No. 2,869,072. W. R. Gieske. Iss. 1/13/59. App. 9/17/53. Assign. The Ford Alexander Corp.

Device for Exploring Ferromagnetic Structure in Well Bores. A device for magnetically testing casing or tubing having a permanent magnet with upper and lower axial extensions forming pole pieces that are wound in opposite directions with coils connected in series to a transformer and indicator.

U. S. No. 2,870,541. F. M. Mayes. Iss. 1/27/59. App. 11/9/55. Assign. Sun Oil Co.

Tubing Caliper. A tubing caliper having around its outer periphery a series of magnetic or capacitative detectors that pick up irregularities in the internal wall of the tubing, each pickup being connected to a diode with all the diodes connected in parallel and the current amplified and recorded.

U. S. No. 2,871,444. R. G. Piety. Iss. 1/27/59. App. 7/20/53. Assign. Phillips Petroleum Co.

Electrical Well Logging. A logging system using a long sonde with three pairs of diametrically opposed semi-cylindrical electrodes, the upper and lower pairs forming guard electrodes to restrict current from the middle pair to a horizontal plane.

U. S. No. 2,872,637. A. Blanchard. Iss. 2/3/59. App. 7/29/53. Assign. Schlumberger Well Surveying Corp.

Electrical Resistivity Well Logging Methods and Apparatus. An electric logging system having above the principal current electrode a pair of potential gradient detecting electrodes connected to an amplifier whose output controls current fed to a auxiliary current electrode.

U. S. No. 2,873,423. J. W. Graham, F. M. Perkins, Jr., C. L. Prokop, and R. A. Salathiel. Iss. 2/10/59. App. 8/22/56. Assign. Jersey Production Research Co.

Well Logging Method. A logging method for detecting hydrocarbons in which a short-spacing electric log is run and the borehole wall subsequently contacted with a material that makes the formation preferentially oil wet and then repeating the log, the material being obtained from a tank on the sonde or by changing the composition of the drilling fluid.

U. S. No. 2,874,301. J. T. Dewan. Iss. 2/17/59. App. 8/10/53. Assign. Schlumberger Well Surveying Corp.

Well Logging Apparatus. A radioactivity logging device using a scintillation counter with photomultiplier connected to an amplifier, differentiating network, and delay line, and having a coincidence counter connected to the delay line and the photomultiplier so as to count only pulses repeated at a known delay and eliminate the random dark-current pulses.

U. S. No. 2,874,347. P. F. Southwick. Iss. 2/17/59. App. 11/2/54. Assign. Gulf Research & Development Co.

Electric Logging. A system for keeping track of movement of a fluid interface in a formation by permanently installing in a borehole a long sonde with a large number of independent electrodes and filling the annular space around the sonde with cuttings from the adjacent formation, electric logging measurements being made on appropriate groups of electrodes in various parts of the sonde and repeated at long-time intervals.

U. S. No. 2,875,347. J. W. Anderson and L. E. Evans. Iss. 2/24/59. App. 12/28/54. Assign. The Dow Chemical Co.

Exploration Tool. A radioactivity logging sonde for ascertaining the attitude of formation fractures into which radioactive tracer particles have been injected and having a radioactivity detector shielded except for a slit down one side, the sonde having a stem with a helical groove that engages a rider with bow springs to provide friction against the borehole wall so that the sonde can be rotated by raising it the length of the stem.

(See also Patents 2,869,071 and 2,874,348 listed under Electrical Prospecting; Patent 2,871,105 listed under Geochemical Prospecting; and Patents 2,871,445 and 2,871,446 listed under Miscellaneous.)

MISCELLANEOUS

U. S. No. 2,867,116. J. S. Aronofsky, G. C. Wallick, and P. P. Reichertz. Iss. 1/6/59. App. 12/27/54. Assign. Socony Mobil Oil Co., Inc.

Method of Measuring Characteristics of Porous Material. A method of measuring the permeability of a core corrected for gas slip in which gas pressure at a plane face of the core is abruptly changed and the resulting transient flow analyzed by measuring the time required for the gas pressure to reach a predetermined value.

U. S. No. 2,867,170. T. A. Kibby. Iss. 1/6/59. App. 6/25/54. Assign. Gulf Oil Corp.

Explosive Device. An explosive assembly having a long metal core with end fixtures to center the assembly in the borehole and with detonating cord wound in a spiral on the core and in a groove cut in the surface of the core parallel to the axis of the core.

U. S. No. 2,867,770. J. R. Tavis. Iss. 1/6/59. App. 12/14/54. Assign. Consolidated Electrodynamics Corp.

Galvanometer Structure. A galvanometer unit in which the suspended system is connected to one end terminal and has a return wire to an annular terminal near the same end.

U. S. No. 2,868,625. W. J. Frank. Iss. 1/13/59. App. 7/22/55. Assign. Jersey Prodution Research Co.

Method of Tracing the Flow of Water. A method of tracing flow in a water flood operation by using a small concentration of ethylenediamine tetra acetic acid as a chemical tracer.

U. S. No. 2,869,058. W. L. Poland. Iss. 1/13/59. App. 5/6/55. Assign. Schlumberger Well Surveying Corp.

Servosystem Function Generator. A three-dimensional function generator having a flexible sheet supported by a rectangular array of screws and defining a cam surface, each screw being in turn connected to a servomotor that rotates the screw until the cam surface conforms to the desired function at the coordinates of the screw.

U. S. No. 2,870,961. G. A. Smith. Iss. 1/27/59. App. 10/29/53. Assign. Sun Oil Co.

Electrical Analogs Employing More than Two Probes. An electrode array for the exploring system

of an electric-conduction-model-type reservoir analyzer using three in-line electrodes parallel to each coordinate axis with the measured potentials combined in a computing circuit to indicate the components of the potential gradient.

U. S. No. 2,871,445. D. H. Carter and R. H. Huddleston, Jr. Iss. 1/27/59. App. 11/30/56. Assign. Welex, Inc.

Well Fluids Resistivity Measurement Apparatus. A circuit for measuring resistivity of fluid in a four-electrode sample cell in which a-c is supplied to the current electrodes in series with the primary of a transformer whose secondary is connected to a calibrated potentiometer and to the potential electrodes through a null detector.

U. S. No. 2,871,446. L. D. Wann. Iss. 1/27/59. App. 1/28/55. Assign. Continental Oil Co.

Wide-Range Resistance and Resistivity Measuring Apparatus. A circuit for measuring resistivity of fluid in a four-electrode sample cell in which a controlled a-c is supplied to the current electrodes from an oscillator and the potential electrodes are connected to an amplifier and indicator, the oscillator output voltage and the amplifier sensitivity being simultaneously adjusted by a common control.

U. S. No. 2,871,473. J. E. Hawkins and L. E. Garrett. Iss. 1/27/59. App. 1/3/56. Assign. Seismograph Service Corp.

Radio Location System. A location system using two end stations and a center reference station and in which interference between the ground wave and the sky wave from the reference station is eliminated by using at each end station two closely spaced antennas for receiving the reference signal, each antenna receiving both waves and connected to a receiver that is balanced for the reference carrier.

U. S. No. 2,871,474. B. W. Koeppel. Iss. 1/27/59. App. 10/16/56. Assign. Seismograph Service Corp.

Radio Location System. A hyperbolic c-w radio location system using position signals from two spaced transmitters and a reference signal from a spaced link station and in which the mobile receiver is arranged to eliminate third frequency errors arising from the spacing of the link station from the position signal transmitters.

U. S. No. 2,872,676. W. R. Hunsicker. Iss. 2/3/59. App. 4/23/54. Assign. Seismograph Service Corp.

Radio Location System. A radio location system using three transmitting stations, two of which radiate carriers intermittently modulated by different pairs of reference signals obtained from the third station.

U. S. No. 2,873,427. J. R. Tavis. Iss. 2/10/59. App. 10/19/53. Assign. Consolidated Electrodynamics Corp.

Suspension Galvanometer. A mirror-type moving-coil galvanometer whose lower suspension is surrounded by a tube closed at the lower end by a terminal cap and with the tube filled with damping fluid.

U. S. No. 2,873,429. R. D. Atchley and W. E. Harrison. Iss. 2/10/59. App. 6/3/53. Assign. Midwestern Geophysical Laboratory.

Magnetic Assembly Having Galvanometers Provided with Adjustable Locks. A multielement galvanometer assembly having a large magnet with concave pole pieces and between which is an adjustable mounting carrying a removable galvanometer case.

U. S. No. 2,874,353. J. R. Tavis. Iss. 2/17/59. App. 10/19/53. Assign. Consolidated Electrodynamics Corp.

Suspension Galvanometer. A mirror type moving-coil galvanometer whose coil has a central glass

stiffener with the mirror mounted on a second stiffener that connects the end of the coil to one of the suspensions.

U. S. No. 2,874,565. F. C. Kelton. Iss. 2/24/59. App. 12/6/55. Assign. Core Laboratories, Inc.

Porosimeter and Method of Measuring Porosity. A device with a calibrated piston for displacing mercury in and out of a chamber that holds a core sample, the bulk volume of the sample being first measured and the system closed and the piston withdrawn to reduce the pressure below atmospheric and the volume measured at a known reduced pressure.

U. S. No. 2,874,602. W. P. Asten. Iss. 2/24/59. App. 3/22/57.

Apparatus for Maintaining Constant the Vibration Frequency of a Tuning Fork. A tuning fork with a drive coil and a pick-up coil connected to a vacuum tube in a self-oscillating circuit and with a bimetallic strip connecting the coils so as to vary their spacing in the same way with either increase or decrease of temperature.

U. S. No. 2,875,401. J. D. Owen. Iss. 2/24/59. App. 9/27/54. Assign. Phillips Petroleum Co.

Core Logging Device. A holder for a long section of core having a series of electrical contacts along its length so that an electrical log of the core can be made by switching contacts.

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Geophysics and the IGY, Hugh Odishaw and Stanley Ruttenberg, Editors, American Geophysical Union, Washington, 1958, 210 pp., $8.00.

Just before the formal opening of the International Geophysical Year on July 1, 1957, the U. S. National Committee for the IGY conducted a special symposium to present and summarize the U. S. program. *Geophysics and the IGY* constitutes the proceedings of that symposium.

Thirty, quite readable papers set forth the plans, goals, and even some early results of USNC participation in IGY. The nature of these papers is such that their earliest possible publication should have been arranged to satisfy the intense public interest in the purposes of the entire program. Most of the papers, despite the publication delay, are nevertheless quite up-to-date and informative. Unexpected changes which have occurred in satellite launching programs are tersely recounted in a May 20, 1958, addendum to John P. Hagen's paper on satellite launching.

CARL H. SAVIT
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Graphic Methods in Structural Geology, Williams L. Donn and John A. Shimer, Appleton-Century-Crofts, Inc., New York, 1958, 183 pp., $4.00.

In this book the authors have aimed toward providing in one text a description of procedures for solving structural problems by use of orthographic and stereographic projections. Its emphasis as a book for undergraduate study is suggested by the fact that approximately one third of the text (Part I) is devoted to a descriptive study of bedded rocks in the form of a brief review.

Parts II and III deal with orthographic and stereographic procedures. These chapters are clearly

written and constitute an exposition of the methods that can be followed with ease. By placing figures opposite the pertinent text, the book permits ready correlation of graphic and written description.

Chapters on the orthographic projection include geometric constructions on true and apparent dip, three-point problems, bed thickness, drill-core problems, plunge, pitch, lineation and fault problems. The stereographic projection methods of Part III deal with the solution of geometric problems where angular relationships are involved. Again, problems such as true dip, bed thickness, and fault geometry are treated, and in addition some problems are examined in which the solution requires rotation of structures into new positions, for example, the restoration of a structure to a position prior to deformation.

Three appendices are included which respectively outline a graphic method for the construction of an ellipse, provide alignment diagrams for computing dip and thickness of strata, and bring together a selected bibliography of twenty-five publications that bear upon material within the text.

When used in conjunction with this bibliographic material, the book should form a useful aid to undergraduate teaching of projection methods in structural geology. Its contents will also be of value to others as a single simplified reference on projection problems in descriptive geology.

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Thermo-Remanent Magnetism and Coercive Force of the Ilmenite-Hematite Series, Seiya Uyeda, *Journal of Geomagnetism and Geoelectricity*, Vol. 9, 1957, pp. 61–78.

This is a very thorough and excellent paper which summarizes the results of measurements of the various magnetic properties of synthesized solid solutions of ilmenite and hematite in varying ratios.

It is pointed out that the natural remanent magnetism of pure hematite has been found useful for paleomagnetic studies because of its extremely high stability and that its thermo-remanent properties have already been studied in fair detail. The importance of the ilmenite-hematite series in rock magnetism is stressed in view of the natural reverse remanent magnetism and the reverse thermo-remanent magnetism found in certain rocks containing this series as their magnetic component.

A series of solid solutions of the ilmenite-hematite series $(1-x)Fe_2O_3 \cdot xFeTiO_3$, with x ranging from approximately 0 to about 0.7, was prepared by quenching powdered mixtures of these two minerals from about 1200°C. No samples were prepared in the range $x>0.7$ since, according to Uyeda, in this range the solid solution is only paramagnetic at room temperature. Measurements were made of the thermal variations of magnetization, remanent magnetization, coercive force and of remanent coercive force by drawing hysteresis loops at successively higher temperatures. Measurements of the stability of the thermo-remanent magnetism were made by means of demagnetization by alternating magnetic field. The dependence of the thermo-remanent magnetism on the intensity of the magnetic field applied during cooling was also determined. All of these measurements were made for each specimen.

Uyeda considers the region ($x<0.5$) to be parasitically ferromagnetic. It seems significant that in this region thermo-remanent magnetism is strong in comparison with induced magnetization, the Q-ratio amounting to several hundred. In the ferrimagnetic region ($0.7>x>0.5$), the coercive force and the Q-ratio are both much smaller. The writer draws particular attention to the fact that remarkable reverse thermoremanent magnetism like that in the Haruna ferromagnetic ilmenites, initially described by Nagata, appears for the specimens of the range bordering the ferrimagnetic and parasitically ferromagnetic regions ($0.6>x>0.45$). This chemical composition is close to that of the Haruna ferromagnetic ilmenite, and, therefore, Uyeda points out that the mechanism which causes the reverse thermo-remanent magnetism may be assumed to be the same for both cases and that the phenomenon is inherent to this range of the solid solution under consideration. He feels that the two-phase hypothesis that has been previously postulated to explain the Haruna-type reverse thermo-remanent magnetism must be reconsidered, since the specimens that he has examined in this study,

have been quenched from 1200°C., which is above the top of the solvus curve of the ilmenite-hematite series. Uyeda concludes on this point that the origin of the reverse thermo-remanent magnetism is closely related with the very fundamental nature of the magnetism of this series itself.

The author has noted a tendency toward reversal in the specimens with x approximately equal to 0.1, which he has termed imperfect reverse thermo-remanent magnetism. He has decided on the basis of experimental evidence that the decrease of thermo-remanent magnetism with decrease in temperature which characterizes these specimens occurs in a higher temperature range than the effective range for production of the Haruna-type reverse thermo-remanent magnetism. Therefore, he concludes that this tendency for reverse thermo-remanent magnetism is not caused by the presence of the component having the Haruna-type reverse thermo-remanent magnetism as impurity. From the same experimental data, he also concludes "that for the production of the imperfect reverse thermo-remanent magnetism, the normally directed thermo-remanent magnetism of the phase having a Curie point at about 560°C. is necessary, and that the phase with lower Curie point is magnetized reversely by some interaction with the already produced normal thermo-remanent magnetism of the high Curie point phase, which is the major constituent of the specimen x approximately equal to 0.1." Uyeda considers that the natural reverse remanent magnetization, reported by Buddington and Balsley, of the Adirondack rocks may be caused by a similar mechanism since they were reported to be hematite-rich ilmenite-hematite solid solutions with exsolution lamellae of ilmenite. He feels that the mechanism producing this natural reverse magnetization may be similar to that producing the imperfect reverse thermo-remanent magnetism in his experiments. The factor that made the mechanism work so effectively in nature is suggested to be extremely slow cooling.

This speculation is certainly very interesting, although the reviewer wonders how it is possible to have two phases developed of this composition if quenched from a temperature above the top of the solvus curve. The author has already ruled out the possibility of the two-phase hypothesis for the reversed specimens partly for this reason. This is by no means offered as a criticism since the reviewer does not understand the details of Uyeda's reasoning leading to this conclusion.

This is recommended as a very significant paper which follows a series on this same general subject authored and co-authored by Uyeda.

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Iron-Titanium Oxide Minerals, Rocks, and Aeromagnetic Anomalies of the Adirondack Area, New York, J. R. Balsley and A. F. Buddington, *Economic Geology*, Vol. 53, 1958, pp. 777–805.

This is an excellent article representing a fine piece of research. It presents information that has been direly needed to combat the many published articles on "fossil" magnetization or what Balsley and Buddington call "periodic reversal." Balsley and Buddington identify another process to account for divergent polarizations and use the term "self-reversal process."

This process results from the study of 200 samples of Adirondack metamorphic and igneous rocks in an effort to relate rock composition to the magnetic properties of the rock. Simply speaking, this study has found that intermediate members of the iron-titanium oxide series, intermediate between magnetite and rutile, are found almost always to have very significant reverse remanent magnetization which in turn gives rise to negative aeromagnetic anomalies. The authors believe that these mineral mixtures have what they call the "self-reversal" property which is an inherent ability to become reversely magnetized. They do not find the process of reversal of the earth's magnetic field fitting the geologic, chemical, and magnetic data of the Adirondack rocks.

Before discussing the article, there is an interesting geologic sidelight occasioned by a short paragraph on pages 797 and 798 in which broad belts of high positive anomalies are identified in the Adirondack area with granitic gneisses. They are contaminated, especially with amphibolite. These were encountered by the author of this review in and around Westchester County, New York, and were used in a geophysical study of the Cortlandt Complex rocks to show that the Complex was

thin in part by the reason that these "gneissic" anomalies ran under considerable areas of the Complex. Again the relations between anomalies and granitic gneisses were encountered recently during an investigation of the pre-Cambrian in south-central Ontario. Therefore, there is a strong possibility that these rocks represent depositional troughs of pre-Cambrian that are widespread, elongated belts having the characteristic marginal strike with respect to older continents of that time.

The concern of this review is not with the quality or the results of the paper under question, but with the matter of having the subject set forth in its proper perspective within the general field of aeromagnetics. A second point is related to this matter of perspective; that is, the paper fails to relate its findings quantitatively to the polarization values of the observed anomalies and to the observed rock distribution.

This matter of perspective concerns those of us who are mapping basement depths throughout the world's sedimentary basins. With those of us who have seen magnetic maps of basement areas throughout the world, there is no question about being able to demonstrate that more than 99 percent of the observed anomalies are caused by induced polarization. Therefore, this article and other articles on the same question tend to create a great amount of undue concern about this problem of remanent magnetization. We know this to be true from the concern shown us by many of the people who are using aeromagnetic data in petroleum exploration. However, we must immediately recognize that a basic difference does exist between the type of survey represented by the Adirondack surveys and the type that results from surveying sedimentary basins. Obviously, this difference is attributable to the greater depth of burial of basement rocks in the latter instance. It is to be granted at once that abnormal polarizations are more frequent over shallow basement than for deep basement, but the necessary conclusion remains that these abnormal magnetizations must be confined to thin rock masses whose anomalies are lost rapidly with depth. The support of this necessary fact cannot be found in the article, and this leads to the second point of criticism.

The second point can be initiated by saying that it is surprising to find negative anomalies of 5,000 gamma resolved by the authors from these Adirondack surveys. It would seem that these anomalies should have been reconciled quantitatively with the observed polarizations and distributions of the different rock types. The only thing we could manage to do to try to evaluate this for an order of magnitude only was to try to relate the probable maximum observable anomaly in these latitudes of $5.0/\Delta I$ cgs to the observed polarizations by applying them to half-spaces. This certainly gave polarizations which fit into the spread of values listed in the article. Nevertheless, the assumption of a half-space for the size of the disturbing rocks is obviously ridiculous, and much higher polarizations would have to be used if correct volumes were used. Our experience leads us to anticipate that the authors would find that these very large negative anomalies are fictitious, having resulted from the regional which was employed. The definition of the regional is undoubtedly the fundamental problem in studying anomalies quantitatively. In a recent instance where we thought we had certainly identified large negative anomalies in the data, subsequent ground studies showed no support of abnormal polarizations but did lead the way toward the correct resolution of the regional. The ground method check is certainly a straightforward way of positively identifying the relationship between aeromagnetic anomalies and surface rocks. Incidentally, the regional value assumed by the authors in the Adirondack Area was an arbitrary constant of 5,000 gamma which could hardly be anything but fictitious.

In conclusion, Drs. Balsley and Buddington are to be distinctly admired for identifying causes of reverse magnetization in the Adirondack Area, but we are quite concerned with the over-emphasis of this phenomenon by not having set it forth in its proper perspective to the overall field of magnetics.

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Magnetism of the Crust, N. Kawai, *Journal of Geomagnetism and Geoelectricity*, Vol. 9, 1957, pp. 140–156.

The author of this paper attempts to draw general rules regarding the distribution and composition of magnetic minerals in the earth's crust and to deduce therefrom the magnetic behavior of rocks

that have crystallized at various depths. Kawai's generalizations are too broad to be useful: It is certainly not true that cubic ferrites (magnetite-ulvospinel series) are restricted to volcanic and plutonic rocks, while metamorphic rocks contain nothing but members of the ilmenite-hematite series. Although there is a general tendency in this direction, exceptions are numerous. In Kawai's view, plutonic rocks are characteristic of pressure-temperature conditions corresponding to the normal geothermal gradient: Nothing is less likely. The author also gives some experimental results on the effect of P and T on the composition of the oxide phases. Unfortunately, he states neither the nature of the materials studied (rocks, artificial mixes, minerals?), nor their initial composition, nor does he allow for oxidation by steam during the runs; thus very little can be deduced from the data. It is also regrettable that his data are presented in such abbreviated form; to give the average remanent magnetization of 436 samples of volcanic rocks is not very helpful, unless one also gives a breakdown as to petrological type, etc.

Some of Kawai's conclusions are interesting, although not necessarily new; he claims to have shown experimentally that at 550°C. and 15,000 atm the iron oxides are dissolved in the silicate phase. He also claims that the titanium content of iron oxides increases with depth in a batholith, although it is not clear whether this is a field observation (where?) or an inference from his experimental work. A general contention is that ferromagnetism will vanish at a depth of about 10 km, because of the gradual decrease in the Curie temperature of the common minerals that results from increasing titanium content. On the whole, the paper deals with an important aspect of petrology and rock magnetism, but it brings to light very little useful information.

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Elementary Seismology, Charles F. Richter, W. H. Freeman and Company, San Francisco, 1958, 768 pp., $12.00.

The prospective reader whose background in geophysics results chiefly from association with the techniques of exploration for petroleum may be misled by the title of this book. Richter's book is not designed to acquaint one with the seismic techniques used in oil prospecting. It is devoted almost exclusively to phenomena associated with natural earthquakes. It is, however, such a unique, comprehensive work on this subject, that nearly every seismologist, regardless of his specialty, as well as many others in allied fields, will want a copy.

Since the book is developed from a lecture course for students in geology who are not specializing in geophysics, mathematics is held to a minimum, but there is a wealth of non-mathematical information. The book is divided into three parts. The first part, entitled "Nature and Observation of Earthquakes," includes such topics as the nature of earthquake motion, foreshocks and aftershocks, general effects of earthquakes with special chapters on effects on buildings and on ground and surface water, intensity, magnitude, types of earthquakes, seismic wave propagation, and seismic theory and practice. Part Two is entitled "Geography and Geology of Earthquakes," and, in addition to world-wide coverage, includes chapters on California, New Zealand, Japan, and Formosa. Of special interest is the chapter on seismology in the U.S.S.R. in which the overall activity of the Soviets in this field through about 1956 is reviewed. Part Three, entitled "Appendixes," contains concise information on a variety of topics including earthquake resistant construction, intensity scales, elastic wave propagation, transit-time tables, calculations of the velocities within the earth, calculations of short distances, and many others. Since this is the only place in which these various pieces of information are assembled, the book is certain to become a standard reference in seismological observatories. *Elementary Seismology* is written clearly and concisely. Material which might have been presented in a dreary and routine manner, appears in an interesting and provocative style, at least partly because of Richter's frank and sometimes witty comments on the subject matter.

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Observation of the Velocity of S-Waves Near the Surface of the Earth, K. Tazime and Hiroshi Okada, *Butsuri-Tanko*, Vol. 11, 1958, pp. 65–70.

The authors are active members of a Japanese group for experimental seismic exploration. This group has been making a series of studies in which the waves generated at some particular places by small explosions are investigated in detail. In the present study, the authors tried to observe the S-waves generated by a simple procedure, one in which a wooden plate buried in the ground was knocked by a hammer in such a way as to generate a shearing force along the surface of the plate. They could not get well polarized S-waves by this method, but they found a predominant wave group which traveled at a very low speed. They identified this wave group as the Love waves and obtained the velocity of the S-wave in the surface layer. The site of the experiment is located near the river Mogami and covered by a soft diluvial deposit. The velocity ratio of the S-wave to the P-wave which was obtained was as low as 0.1 to 0.2, giving a Poisson's ratio of 0.48 to 0.49.

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A Solution of Separation Surfaces on the Seismic Reflection Method, Ryuzo Adachi, *Butsuri-Tanko*, Vol. 11, 1958, pp. 75–78.

The problem in this study is to obtain the depth $z(x, y)$ of a boundary surface as a function of the co-ordinates x and y when the reflection time $t(x, y)$ is given as an arbitrary function of x and y. The velocity of the wave is assumed to be constant throughout the upper layer. The result is given in a parametric form in which x, y, and z are expressed in terms of the reflection time and its first derivatives. This study, interesting at least from the mathematical point, will have some practical importance if a solution is obtained in the case of velocity increase with depth within the surface layer.

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Seismic Apparatus for Prospecting in the Drifts, Takefumi Toba, *Butsuri-Tanko*, Vol. 11, 1958, pp. 71–74.

The author is interested in the use of very high frequency elastic waves in prospecting mines. A description is given of a seismometer which is designed specifically for this purpose according to the idea of Dr. Sassa. In this seismometer, the mass is supported by rubber plates and the natural frequency is about 10,000 cps. The amplifier connected to the seismometer is designed to have an amplitude characteristic inversely proportional to the square of frequency in order to compensate the attenuation of elastic waves which depends on frequency.

In a preliminary experiment, he recorded vibrations of 500 to 1,500 cps generated by a dynamite explosion in a rock, and some of the phases are identified as reflections from known boundaries.

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Two-Component Capacitance-Type Displacement Detector, John A. Rider and W. L. Roever, *The Review of Scientific Instruments*, Vol. 29, 1958, pp. 951–961.

This paper describes a two-component displacement detector that is especially suited to seismic model work. The detector consists of two probe capacitors and a common ground plate. The probe capacitors are part of resonant circuits of oscillators such that the vertical and horizontal components of displacement of the common ground plate can be observed as the sum and difference frequencies of the two oscillators. The circuitry and the principles of operation of the detector are given in detail. The detector has high sensitivity and the noise levels of the horizontal and vertical components are less than 10^{-3} microns for a bandwidth of 550 cps to 140 kc.

This type of detector combines several features that are important in model seismology. It is small so that scale factors can be maintained; the mass of the put of the detector that is on the model can be very small, and the detector should not become a source of diffracted waves due to its presence. The latter can be a serious problem if one is studying thin plates and 2-dimensional seismic models.

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Introduction to the Theory of Sound Transmission, C. B. Officer, McGraw-Hill Book Company, Inc., New York, 1958, 284 pp., $10.00.

This volume is a lucid account of the applications of acoustical theory to the propagation of sound in the sea. It will be of value both to those in the field of underwater sound and to the geophysicist. It is self-contained and provided with an extensive bibliography. Since it deals primarily with wave propagation in fluid media, it is an excellent companion to the book *Elastic Waves in Layered Media* by Ewing, Jardetzky, and Press (McGraw-Hill, 1957).

In the first two chapters, the author discusses the fundamental theory necessary to an understanding of the special problems taken up later in the book. Both wave and ray solutions of the wave equation are treated, and the reader is introduced to the notions of normal mode solutions and dispersion.

Next in order come the chapters on shallow water and deep water transmission. In the first there is given a detailed account of the Pekeris theory of normal mode solutions. This is followed by a brief account of the dispersion for "leaky modes" that should be of considerable interest to those concerned with "ringing" in shallow water areas where there is a substantial impedance mismatch between the water and the sedimentary layers beneath. In the chapter on deep water transmission, Sofar channel transmission, normal mode solution for the case of a solid bottom, and near surface transmission are discussed.

The remainder of the book deals with reflectivity and attenuation. The topics considered include reflection and transmission coefficients, interpretation of echo soundings, seismic refraction and reflection, porous media, and diffraction effects.

There are a few minor errors in the text and a more serious one in equations 5-126 and 5-127 where $\bar{b}$ in both numerator and denominator should appear as $\bar{b}^2$. In general, the book is well written. The author has been careful to provide physical interpretation as well as mathematics and to preface each main topic with an account of the environmental situation.

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Transactions American Geophysical Union, v. 40, n. 1 (March, 1959)

ABSTRACTS FROM *GEOPHYSICAL PROSPECTING*

Official Journal of the European Association of Exploration Geophysicists*
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The causes of geophysical accidents

H. RICHARD

The attention of everyone has already been drawn to the part which accident reports must play (*Geophysical Prospecting*, March 1957, pp. 1 to 8). We intend to show here, with supporting examples, that the systematic analysis of the causes, does allow one to obtain practical conclusions.

To begin with, it is advisable to widen the notion of geophysical accident as much as possible. This being done, about 200 reports distributed over a long period and a sufficient number of parties, are dealt with. The collected reports are sufficiently numerous to draw conclusions in a general way bearing on the headings: drilling, transport, outbreaks of fire, explosives, falls, stings, shocks, miscellaneous causes.

All the quoted figures are referred to the number of accidents reported. Action must be taken to encourage European geophysicists to study accident reports and to analyze the causes. This may be done in such a way that secret information, such as whereabouts of their personnel, is not disclosed.

Efforts to promote "Security" must in the first place bear on the quest for the causes, the definitions of "accident" and of "geophysicist" being taken at their widest possible meaning.

Some model experiments relating to electromagnetic prospecting with special reference to airborne work

E. H. HEDSTROM AND D. S. PARASNIS

After a discussion of the underlying principles, some electromagnetic model experiments made primarily in connection with the development of the ABEM airborne method are described. The experiments were made on thin vertical and horizontal conductors of "infinite" extent with coil arrangements involving one transmitter and one receiver unit. The in-phase and out-of-phase components of the field picked up by the receiver were measured in percent of the amplitude of the normal field at the receiver. In this case 1° phase-shift corresponds to 1.75% of the normal field amplitude. The experiments were made on a scale 600–2,000 times smaller than the natural scale. The ores and overburdens normally encountered in the field were simulated by sheets of Cu, Al, Zn and Pb of varying thicknesses. The frequencies used were 500, 880 and 1,500 c/s. The variation of the secondary fields with the thickness, resistivity and depths of the conductors causing them is discussed in some detail. The bearing of the laboratory work on ground and especially airborne electromagnetic methods is indicated. A few miscellaneous experiments are also described. The results of an airborne survey over a known ore body and those of the corresponding model experiments are given. The ABEM airborne electromagnetic method and the so-called "Canadian" method are briefly compared in the light of the model experiments described.

On the theory of gamma ray scattering in boreholes

J. HOMILIUS AND S. LORCH

This paper deals with the theory of the gamma ray scattering method, which is applied in determinations of density, mainly in boreholes. In this method, the gamma radiation from a radioactive source is scattered round the borehole, and recorded by a detector which is protected against direct radiation by lead.

The theory is based on the scattering and absorption properties of matter with regard to gamma radiation, as described by the Klein-Nishina formula in terms of the quantum theory. The single scattered portion of radiation, which is of particular importance, is calculated. In doing this an absorption dependent on the scattering angle, and a counter efficiency dependent on the energy of radiation and the angle of incidence, are taken into account. The range of the detector can also be considered.

* 30, Carel Van Bylandtlaan, The Hague, Netherlands.

For homogeneous soil, the dependence of the counting rate on the distance between source and detector, on the density, and on the screening of radiation by the lead absorber, is investigated.

Furthermore, the scattering range for various soil densities and distances between source and detector is also determined. The existence of a substantial degree of agreement between theory and experimental findings is demonstrated. Results are compared with those of the DJADKIN diffusion theory, and are illustrated by means of examples of the gamma gamma probe and the gamma density meter for surface measurements.

On reflected refraction waves

W. BRAUCH

As an introduction the various ray paths of a refraction wave, which is reflected at a fault, are discussed for the case of an arbitrary angle between the refracting horizon and the fault. Simple geometric considerations lead to the conclusion that the best chances for recording these pulses are encountered, if the angle between the refracting horizon and the fault is either 90° or the critical angle of refraction. In both cases identical travel times of the pulses are to be expected.

The case of a fault perpendicular to the refracting horizon is considered in detail for dipping beds. Formulas for the shot point travel time curve and the time contour map are derived. Computed time contour maps show considerable differences between the direction of strike of the contour lines and the strike of the fault, as well as between the recorded apparent velocity and the true velocity of the refracting horizon. Finally, alignment charts and computing procedures are given by which the position of the fault and the velocity of the refracting horizon can be obtained from the recorded shot point travel times or the time contour map.

Seismic model experiments concerning reflected refractions

O. KOEFOED, J. G. VAN EWYK, AND W. T. BAKKER

Seismic model experiments are described in which long strips of plexiglass were used as models. One end of the strip was sawn off at an oblique angle and, at the opposite end, the strip was excited by means of a barium titanate transducer. The experiments showed that, if the width of the strip was sufficiently small, an anomalous reflection against the oblique end occurred which travelled in the longitudinal direction of the strip. This anomalous reflection did not occur when the width of the strip was large. These results are explained on the basis of Fresnel's theory. It is inferred that, in the subsurface, refracted waves may be reflected against fault planes without the law of reflection being satisfied, provided that the refracted wave is propagated in a sufficiently thin high velocity layer.

SYMPOSIUM ON CHANGES OF SHAPE OF SEISMIC PULSES

Why all this interest in the shape of the pulse?

N. A. ANSTEY

Theoretical work on seismic pulse propagation must, of necessity, use advanced mathematical methods. To the general reader these researches may seem far removed from the necessities of commercial geophysics; this paper attempts to show in nonmathematical terms that the basic potential of the seismic method permits the obtaining of considerably more information than is currently expected, and that, of all the advances which are required to realize that potential, a knowledge of the laws governing the transmission of the seismic pulse is most desired.

Attenuation of shear and compressional waves in Pierre shale

F. J. MCDONAL, F. A. ANGONA, R. L. MILLS, R. L. SENGBUSH, R. G. VAN NOSTRAND, AND J. E. WHITE

Mr. Van Nostrand gave a re-presentation of the paper which has been published in GEOPHYSICS, v. 23, 1958, p. 421–439. For detailed information reference should be made to GEOPHYSICS.

The influence of a layer complying with a linear velocity law on the shape of seismic pulses

H. MENZEL AND O. ROSENBACH

A layer with parallel plane boundaries is assumed to have a constant density and exhibit a velocity of propagation of seismic waves which increases linearly with the distance from one boundary plane. The influence of this layer on the shape of seismic pulses is investigated in two different cases, in which:

1. The layer is embedded between two media each of which has a constant density and velocity of propagation.
2. The layer is adjacent to one medium of constant density and velocity; i.e. one boundary plane of the layer is the free surface of a two-layered elastic half space.

Through one medium with constant velocity a plane compressional wave impinges at normal incidence on the layer complying with the linear velocity law. The incident seismic pulse is therefore split up into reflected and transmitted parts, the elastic motions of which are studied in the neighborhood of the layer. The mathematical solution can be deduced for a general pulse by using the Laplace-Transformation. The general solution reveals that the layer following the linear velocity law influences the shape of the reflected and transmitted pulses. This influence is discussed in detail by demonstrating some numerical examples.

A note on the seismic pulse recorded from a mine explosion

N. A. ANSTEY

It is not easy to record a seismic pulse at distances of interest to oil prospectors without there being reflected or refracted pulses superimposed on the direct arrival. Accordingly the record illustrated is considered worth publishing, although it was taken fortuitously during a normal survey and cannot claim to be a controlled experiment. A comparison with the filtered pulse to be expected from a theoretical Ricker-type wavelet is presented.

Changes of shape of seismic impulses in homogeneous viscoelastic media

G. W. POSTMA

Changes of shape of seismic waves provide information on the properties of the material in which the waves propagate. Ricker (1953) has attempted to explain the changes of shape on the basis of a simple viscoelastic theory. His conclusions are at variance with those of others who find a dependence of the attenuation on frequency which could be explained only by a much more complicated linear theory or by nonlinear theories.

To provide a basis for discussion, the essentials of the theory of viscoelasticity are briefly reviewed. If a relaxation spectrum, rather than one or very few relaxation times, is admitted, a great variety of experimental results can be described by the linear theory of viscoelasticity. A linear theory is indicated when no obvious violations of the principle of superposition occur.

Ricker's theory is presented with some modifications which allow for a finite duration of the initial pulse and for the approximate character of his basic assumptions. There do not appear to be serious discrepancies between his theory and his experimental results. Some of the objections to his theory can be met by assuming a finite duration of the initial pulse. However, more direct measurements made under similar circumstances by McDonal *et al.* (1958) at the same location lead to a conclusion on the nature of the material not in accordance with Ricker's. This casts doubt on the sensitivity of his method.

Laboratory measurements usually yield results which are not explainable in terms of simple viscoelastic models. Whether a linear theory with a relaxation spectrum or a nonlinear theory should apply depends much on the experimental conditions. We must also consider the possibility of nonlinear mechanisms which are active at small amplitudes. No stand is taken in this controversy, but it is pointed out that the question linear or nonlinear could be decided experimentally without considering the details of the theories.

MEMORIALS

JACK MARTIN

On July 25, 1958, JACK MARTIN died at Presbyterian Hospital in Denver, Colorado. Burial was at Fairmont Cemetery in Denver. Jack's death was a tremendous loss to the petroleum industry and to the geophysical and geological professions.

Jack was born in Rogers, Arkansas, on September 18, 1919. He entered school there in September, 1926, and graduated from high school in June of 1938. He entered the University of Arkansas in September of 1938 and graduated with a B.S. in Geology in June, 1942. Jack first acquired the great love he later showed for the earth sciences here at the University.

Jack was married to Bette Lloyd of Rogers, Arkansas, on May 15, 1942, and they had one son, Ronald.

Jack began employment with General Geophysical Company as a computer trainee in February, 1942. He was stationed at various places in Texas, Louisiana, and Mississippi until he was promoted to party chief in 1945. The same year he was transferred to Kemmerer, Wyoming, and in 1948 he was promoted to regional supervisor located at Casper, Wyoming. He moved to Denver, Colorado in 1949 where he lived until he died.

Jack was a great competitor, had a very fruitful, imaginative, and productive mind. His love of geology and geophysics and the new ideas he developed in these subjects caused him to be admired by all of his business associates. The last year of his life he developed and promoted the use of ammonium nitrate as an explosive

for geophysical purposes. This has brought about tremendous savings in seismic exploration.

As soon as he moved to the Rocky Mountain country, he fell intensely in love with it—perhaps because he could see such wonderful expressions of his beloved geology on the surface. Here, too, he could enjoy the fishing and hunting which, with golf, were his principal sources of recreation. We believe that these same Mountains mourn the passing of a fine gentleman, husband, and father.

T. O. HALL

HOUSTON, TEXAS

RAYMOND USTICK McKINNEY

RAYMOND USTICK McKINNEY died in Tulsa on December 10, 1958, of cancer, from which he had been suffering for more than a year. He had retired two months before this from Wood & Miller Engineering Company, where he was employed as a geophysicist.

Raymond U. McKinney was born December 25, 1907, in Moberly, Missouri. His father was George Ustick McKinney; his mother the former Bessie Canole. He was married in Sapulpa, Oklahoma, November 29, 1934, to Burmah Baker. John Baker McKinney was born to them in November 1935. He attended Tulsa University, and the University of Oklahoma, where he studied geology, during the years 1926, '27, '28. Ray was a member of Pi Kappa Phi fraternity.

Ray worked for a while as a radio operator, and was an ardent ham operator

during his spare time. In 1933 he went to work for Seismograph Service Corp. and remained there until 1939 when he went into business for himself. He did consulting work for many years, but worked for prolonged periods for Geophysical Engineering Company, Cities Service Oil Co., James Shelburne, and others, as a geophysicist.

Ray was instrumental in the discovery of a number of oil pools in East Central and North Central Oklahoma, and during his last few years maintained maps and data on practically all of the northeastern quarter of Oklahoma. He prognosticated a number of new pools which will likely be tested in the next few years.

Ray invented and developed a number of devices and systems applicable to seismic and other geophysical field work, and for surveying. He did a number of consulting design jobs on geophysical equipment, seismic well logging, etc., and a lot of field work testing such devices.

Ray McKinney is survived by his wife, Burmah, his son, John, and an aunt, Mrs. C. W. Markley, of Tulsa. He was a member of the Elks, and the SEG. He was a charter member of the Sequoyah Yacht Club of Tulsa.

I remember Ray as a warm hearted, pleasant, hard working and hard playing character, with many friends. He liked most people. He was a good geologist and a good geophysicist. In departing this world he certainly has left behind him footprints on the sands of time.

W. G. GREEN

TULSA, OKLAHOMA
January 8, 1959

JOHN LAURIN MARTIN

JOHN LAURIN MARTIN died very suddenly of a heart attack March 22, 1958 at the age of 32. His death came as a great shock to his family, his friends and co-workers. John Martin was an outstanding engineer destined for a bright future. At 27 he had achieved a supervisory position as the head of well logging research for The Atlantic Refining Co.

In 1956 he, together with W. M. Campbell, received the Cedric K. Ferguson Medal awarded by the American Institute of Mining, Metallurgical, and Petroleum Engineers for the paper entitled "Displacement Logging—A New Exploratory Tool." This is the top award offered by the AIME for professional contribution by a young engineer.

Born August 20, 1925, in Wichita Falls, Texas, John was the son of a drilling contractor. After completing grade school in Wichita Falls, he attended and graduated from high school in Fort Worth. John spent his college freshman year at Arlington (Texas) State College. In 1943 he transferred to Georgia School of Technology and completed his B.S. and M.S. degrees in electrical engineering there, interrupted by a period of service in the Navy during 1945–46. His honors included Tau Beta Pi, Eta Kappa Nu, Phi Kappa Phi, and Omicron Delta Kappa.

Mr. Martin had been a member of the SEG since 1948. He was also a member of the AIME and American Institute of Radio Engineers.

John Martin started to work for Atlantic in September, 1947, in the Research and Development Department. His initial work was in seismology research and downhole instrumentation problems. In 1952, he became supervising engineer in charge of well logging research for Atlantic, the position he held until the time of his death. His friendliness, ability, and integrity will be an inspiration to all of us who knew and worked with him.

H. F. DUNLAP

DALLAS, TEXAS
March 10, 1959

MATTHEW T. MURRAY

MATTHEW T. MURRAY, geophysicist for Standard-Vacuum Oil Company, died of a coronary thrombosis on Thursday evening, May 29, 1958, at his home in Port Chester, New York. Funeral services were held on June 3.

"Matt," as he was called by his friends and associates in the petroleum industry, was 47 years old and normally could have expected many more years of enjoyment in his chosen profession of geophysicist and his favorite hobby of boating. He and his wife had prepared for a long weekend on Long Island Sound in their 27 foot motor launch, and "Matt" was reading a technical journal after the evening meal when he was stricken with the sudden and fatal heart attack.

"Matt" was born on August 2, 1910 in New York City and attended grammar

and high school in Long Island. He received a degree in civil engineering from Manhattan College of New York in 1935 and took postgraduate work in geophysics at Colorado School of Mines during 1943.

He began his geophysical career in 1937 with General Geophysical Company in seismic exploration. He was employed on gravity meter work by Mott-Smith Corp.; on electrical exploration surveys by Elflex Company; carried out gravity and magnetic surveys with the Heiland Research Corp.; worked in several branches of geophysics with Geophysical Exploration Company and supervised seismograph and gravity meter surveys for the Chilean Government.

In 1951 "Matt" joined Standard-Vacuum Oil Company in India to supervise an airborne magnetometer survey of the Bengal Basin. He remained with Standard-Vacuum until his death, having served as supervisor and interpreter on seismic, gravity and magnetometer surveys in India, Pakistan, Indonesia and Australia. He was transferred to the White Plains office in February 1958.

His passing is keenly felt by his many friends within and without the petroleum industry. "Matt" always attacked each problem, whether in business or in recreation, with great enthusiasm and had a capacity for mental or physical activity commensurate with his splendid physical development.

"Matt" is survived by his wife Gretl, whom he married in 1936; by a sister, Mrs. John Hartel, and by his mother Mrs. Margaret Murray of Flushing, L. I.

GODFREY F. KAUFMANN

WHITE PLAINS, NEW YORK
June 16, 1958

JOHN EDWARD LEE, JR.

JOHN EDWARD LEE, JR. died unexpectedly of a heart attack November 22, 1957 at Denver, Colorado. Apparently he was enjoying good health when he left his home in Lafayette, Louisiana to attend the funeral of his wife's only sister. The news of his untimely death came as a great shock to his family and many friends. Interment was in the Lafayette Memorial Park at Lafayette, Louisiana.

Jack, as he was better known, was born August 23, 1913 in Denver, Colorado. In 1933 he married Helen Bernice Parmeley. He attended Colorado School of Mines where he was graduated in 1937. He was a Phi Beta Kappa member.

After graduation from college, Jack started his career in geophysical exploration as a geophysicist for Heiland Research Corporation in Denver. In 1940 he joined the Kerr-Lynn (now Kerr-McGee) oil company as chief geophysicist and travelled extensively for the firm until 1946. During this year he was an organizer of Lafayette Exploration Company (formerly American Exploration Company) later organizing wholly owned subsidiaries, the Lafayette Exploration Company of Mexico and Lafayette Exploration Company of Nicaragua. The firms have conducted considerable marine petroleum exploration throughout the world, having pioneered in offshore exploration work in the Gulf of Mexico and Bay of Campeche. The company operated exploration programs in the Gulf of Mexico, Mexico, South America, and the Persian Gulf.

JOHN EDWARD LEE, JR.

In 1949 he became an organizer of Petroleum-Helicopters, Inc. (formerly Petroleum Bell-Helicopter Services, Inc.); a company organized for the purpose of expediting the movement of supplies, equipment and manpower of seismic operations offshore and in marshlands where transportation is normally a time consuming problem. He divested himself of this interest in 1953.

An avid fisherman and hunter, he shared his hunting and fishing trips, techniques and pleasures with employees, friends and associates.

At the time of his death he was a member of the board of directors of the First National Bank, Lafayette, Louisiana and its discount committee. In addition to being active in the Society of Exploration Geophysicists, Jack held membership in the American Association of Petroleum Geologists, Southwest Louisiana Geophysical Society, Southeastern Geophysical Society, Lafayette Geological Society, the Petroleum Clubs of Lafayette and Houston, the Colorado School of Mines Alumni Association, Rivers Bend Country Club and Oak Bourne Country Club.

Jack is survived by his wife, Bernice and three daughters, Mrs. Pierre E. (Diane) Conner of Virginia, and Sandra Jean and Judith Ann at home.

H. R. CONLEY

LAFAYETTE, LOUISIANA
January 8, 1959

LETTERS TO THE EDITOR

DISCUSSION ON "THE PREPARATION OF A PAPER"

The fine article on the "Preparation of a Paper" by Dr. L. Y. Faust is very timely, coming as it does on the heels of an annual convention which suffered considerably from a less-than-perfect overall quality of oral presentation. However, I must state that I cannot agree with Dr. Faust's method of preparation of oral and finally written papers.

The following objections are raised:

1. Very few, if any, scientists can make a sound oral presentation without first having written out, in manuscript form, the results of their findings. "Visual digestion" of the significance of various aspects of his work makes a much greater impact on the scientist than "oral digestion." In fact, I sometimes feel that many of our best geophysicists suffer from "oral indigestion," as a result of insufficient cogitation. Effective thinking can seldom be accomplished without writing out the facts, assumptions, conclusions, and recommendations.

2. A busy geophysicist—which means one who is *effectively* employed—can seldom spend the time to prepare an oral paper as thoroughly as suggested by Dr. Faust *and* then prepare a written paper on the same subject. I agree that numerous revisions of script are required before a good paper can result. Yet I ask myself, "Is it really necessary to prepare the same paper a second time, and thereby risk the possibility of frustration at repeating a job on the most important presentation, the written one?"

3. From the program chairman's viewpoint, obtaining technically good papers is a difficult and time-consuming chore. Why discourage these "peones" by suggesting that they pressure their potential authors into the laborious "oral then written" sequence encouraged by Dr. Faust.

I am forced to agree with Dr. Faust that he who follows the printed instructions will " . . . deserve the Best Paper Award!" However, I do think that the approach is idealistic.

On the constructive side I would like to suggest the following point-form sequence:

1. Prepare written manuscript with illustrations following Dobrin (1954) faithfully.
2. Have associate, intimately acquainted with subject, edit and criticize.
3. Have scientist remote from subject criticize from "ease of understanding" viewpoint.
4. Have expert on English grammatical construction smooth out manuscript or offer criticisms. Rewrite manuscript again following Dobrin (1954).
5. Shelve manuscript for period of one week minimum and preferably much more. Then collect illustrations into an appropriate sequence for oral presentation. Add slides to take care of concluding mathematical formulae, tables, important conclusions, etc.
6. Make short hand notes for oral presentation.
7. Practice oral presentation once to clean up details.
8. Relax and speak off-the-cuff from your slides to your *friends* at the meeting.
9. Immediately subsequent to meeting amend manuscript to take advantage of criticisms arising at meeting. Then mail 2 copies to the Editor, GEOPHYSICS.

STANLEY H. WARD
Toronto Canada

REFERENCE

Dobrin, Milton B., 1954, Style guide for GEOPHYSICS: GEOPHYSICS, v. 19, p. 141–153.
Received by the Editor January 25, 1959.

AUTHOR'S REPLY

Dr. Ward's criticisms are appreciated and should prove useful. He may be correct in some of his objections although it is doubtful to this writer that all of his criticisms have equal validity.

Objection 1 would be a valid objection if any different position had been taken in "Preparation

of a Paper." The second assumption in the imagined sequence for preparation of an oral presentation was: "You have received clearance and encouragement for 'giving a paper'." (Since I am several thousand miles from the nearest copy this may not be an exact quotation.) With few exceptions anyone in that position would have been required first to submit his findings in a report to his company or clients either verbally or in written form. If a prospective author had not thoroughly digested his material before such submission we would hesitate to offer him further advice. A report, however, is not a paper. Those obvious company reports that have been submitted to the Editor of GEOPHYSICS have required almost complete rewriting and reorganization before acceptance. We agree therefore with the main thesis of Objection 1, but insist that this process does not usually result in a manuscript acceptable for publication nor a satisfactory organization for oral presentation.

Objection 2 may be true in some cases but not universally. We know on the best of authority of several papers which have been prepared in this manner although whether by one "*effectively* employed" may conceivably be conjectural.

Objection 3 is one whereon Dr. Ward is well qualified to speak. As Program Chairman for the Mining sessions of the ensuing 29th Annual Meeting, he has a difficult task.

We will make no great objection to Dr. Ward's preferred order of constructive suggestions despite our preference for a reversal to an oral-written sequence. However, certain details of the suggestions seem inadequate or even objectionable. Constructive points 1–4 are not in themselves at variance with our own suggestions. However the implication that one rewriting of the manuscript is sufficient for the average scientist-author is contrary to our experience. We doubt that such hasty preparation could even put the manuscript in shape for a rewriting by the Editor—a chore with which he is surfeited. A published scientific paper is a monument to the author. He should be willing to spend some time in making it worthy.

There is little difficulty in interpreting the second sentence of Constructive Point 5 and all of 6 as being in agreement with the idea of rearranging the material specifically for oral presentation. The suggestion however of presenting tables as slides is abhorrent to this writer. Except in the case of the most simple ones they cannot be read by an audience. Tables offer a ready accessibility to useful data which the brief flashing of a slide on a screen does not fulfill. Tables are most appropriate in the lasting contribution of a published paper. Indeed, one could seek no better example of the considerable difference between the approaches of an oral versus a published paper.

Without wishing to be sarcastic concerning Constructive Point 7, we have had nightmares in which we found ourselves attempting to deliver a speech practiced only once.

We are in whole-hearted agreement with Point 8. We suggest however that the probability of being able to relax might be increased by the assurance of adequate preparation.

With respect to Point 9, we hope that authors following Dr. Ward's plan will resubmit their manuscripts once more to critics of their choice and then rewrite again and preferably again.

The introductory paragraphs of "Preparation of a Paper" explained that the procedures to be suggested were one way of preparing a paper, not the only one. A study of Dr. Ward's Constructive Points suggests that there exists a more or less general agreement in principle.

However Dr. Ward, while deprecating the overabundance of poorly prepared presentations, believes that the minimum preparation he suggests would be adequate. Evidently too many of our speakers have shared that belief.

LAWRENCE Y. FAUST
Mogadiscio, Somalia, Africa

WARD'S REPLY

Dr. Faust has taken an admirably firm stand in defense of the principles which he feels are essential to "The Preparation of a Paper." Obviously his greater experience in such matters must be appreciated.

Of particular importance to the discussion is his comment, "If a prospective author had not thoroughly digested his material before such submission, we would hesitate to offer him further advice."

Unfortunately people who have not thoroughly digested their facts *do* appear upon the doorstep of the Program Chairmen. It is with these individuals that I am concerned.

Concerning the main points of Dr. Faust's objections to my constructive suggestions, it would appear that I have been guilty of a major literary crime. My own writing of the "point-form sequence" is not adequately clear to Dr. Faust. I left to inference the necessity of the author's rewriting the manuscript after steps 2 and 3, as well as after step 4. I think that this many revisions are in order, but not ten or more as inferred in Dr. Faust's original manuscript. If an author cannot achieve a polished manuscript after four revisions based upon critical reading by several acquaintances, then generally he has not adequate training in English composition to consider writing a paper for publication. In our present quickly-moving world we must learn to communicate in an efficient manner.

On two other points, Dr. Faust and I are obviously in complete disagreement. Firstly, tables of topics or facts, and *simple* formulae can be presented on slides yet serve a very useful purpose, *provided* the slides are prepared according to accepted standards such as those outlined by Dobrin (1954). Secondly, a speech that has been rehearsed more than two or three times, more often than not lacks spontaneity; this, in my opinion, constitutes a greater evil than a somewhat hastily rehearsed talk.

If these comments serve to draw the attention of potential speakers and authors to the necessity of serious thought on preparation of a paper, then my primary objective will have been fulfilled. It is hoped that the potential speaker realizes this limitation and prepares for his talk in a manner best suited to his personality, capabilities, and experience. For those unable to evaluate their limitations, Dr. Faust has provided a very thorough procedure which will at least lead to an *acceptable* oral presentation by even the most ill-adapted.

I wish to thank Dr. Faust for his kind consideration and reply to my comments.

STANLEY H. WARD
University of California
Berkeley California

Received by the Editor March 9, 1959.

SOLICITED COMMENTS ON WARD'S DISCUSSION

At the Editor's request, I comment herewith on the discussion of Dr. S. H. Ward concerning "The Preparation of a Paper."

It appears to me that Dr. Ward is in the position of defending the usual, casual approach to the writing and delivery of a technical paper. The obvious short cut is simply to write a paper, have slides made of the figures, and then to speak off-the-cuff about the slides to your friends at the meeting.

This method requires an expert in the art of delivery; it is precisely the purpose of Faust's paper to eliminate repeated attempts to be such an expert. Only a very small percent of people are endowed with the ability to speak lucidly and clearly "off-the-cuff," no matter what their knowledge of the subject may be. Often the clarity decreases as the speaker's knowledge increases, for he tends to neglect the simple fundamentals in favor of the nuances and high level findings that intrigue him at his lofty summit of knowledge. Also, few of us manage to remember, in the fluster of presentation, all the really essential things which should be said on the subject discussed.

Faust's method brings a passable, or adequate presentation within the reach of all speakers. It is based on the absolute truism that a spoken presentation and a technical paper are entirely different. If a man is going to present a paper orally, then that speech deserves all the preparation necessary to make it a good speech, quite aside from the technical effort involved in the paper.

As a matter of fact, it is hardly possible for the average man to relax as he speaks, as Dr. Ward would rightly have him do, unless he is well prepared. The prepared oral speech is the only means of guaranteeing a measure of relaxation to the vast majority of us who will never be orators, simply because we were not made to be orators without tremendous effort. Off-the-cuff speaking ranks as one of the most difficult human problems.

The prepared oral speech may be the lesser of two evils, but it is a safe bulwark on which the entire technical meeting can be based, for a level of speaking performance is assured. By contrast,

more than half of the "off-the-cuff" speakers will make somewhat dismal efforts, and these failures will drag down the entire meeting.

I'd like to reserve Dr. Ward's method for the truly expert speakers; let all of us ordinary mortals adopt the safety measures of Dr. Faust.

PAUL L. LYONS
Tulsa, Okla.

Received by the Editor February 27, 1959.

GEOPHYSICS YEARBOOK

I've just received the 1958 yearbook issue of GEOPHYSICS. Now that we're compiling five issues per annum may I register a "scream" of protest at the amount of non-documentary material that is being volumized.

Out of 352 pages in this issue, not more than approximately 100 pages of these are of any documentary value. I don't know about the other members but I have all these bound into library editions for safekeeping. It seems rather absurd to bind supplementary indexes of wells shot for velocity (probably to be published later); newspaper type accounts of annual meetings, etc; abstracts of papers presented at such meetings (probably to be published for documentation later); reviews of publications received; and especially membership lists.

I'm not objecting to this material being presented, but rather to its being included for binding.

I would also like to suggest that the first article in each *volume* be the SEG Constitution and Bylaws (as currently amended) and the last article in each *volume* be the Annual Report. Actually I think that all the data currently indexed under "Departments" with the exception of "Contributors" not be documented. "Contributors" would be an appropriate closing article for each *issue*. In this manner our magazine would be a concise publication of complete technical articles only without taking on the appearance of a news magazine when it gets back from the binders.

Perhaps I'm being overly critical but by the time my copies of GEOPHYSICS are bound everything except the *strictly complete articles* and their authors is either outdated or of no lasting value.

JENNINGS G. SMITH
Western Geophysical Company of America
Anadarko, Oklahoma

Received by the Editor January 23, 1959.

REPLY BY SEG BUSINESS MANAGER

On page 212 in the January 1957 issue of GEOPHYSICS you will find a report on the proposed annual issue. The recommendations in this report were adopted by the Council at its meeting in New Orleans on October 29, 1956. Although some modifications have been necessary in the form and content, you have found that the Yearbook does carry out its main purpose of collecting non-technical information, or "non-documentary material," that previously had been published in other issues throughout the year. Our constitution and bylaws require publication of the membership list and constitution, as well as the reports of the committees. Many of our members had complained that the April issue containing the membership list received quite a beating and was unwieldy. They wanted to isolate this non-documentary material both for easy reference and possible elimination when they bound their volumes. Also, the volume of technical contributions to the Journal, "our most important product," was increasing. It was apparent that we would need to publish GEOPHYSICS more frequently to accommodate this growing wealth of technical information.

The Yearbook was the first step. By isolating the non-technical information we were able to devote more space in the four regular issues to technical papers. Also we were provided additional revenue from advertising to offset the cost of publishing the membership list. Our next step will be taken in 1960 when GEOPHYSICS will be published six times a year. By moving into the more frequent publication in stages, we expect to be able to provide the advantage of a bi-monthly Journal at no increase in membership dues.

So the publication of our Yearbook actually is an attempt to do just what you are asking. May I suggest that before sending your volume to the bindery you simply remove the unwanted pages from the Yearbook issue? I am sure you will find this much better than having to remove unwanted material from every issue as previously. Again, let me thank you for your comments. I hope you will continue to let us have the benefit of your thinking; that is the only way we can improve our service.

COLIN CAMPBELL
Tulsa, Oklahoma

Received by the Editor January 23, 1959.

CONTRIBUTORS

ZBIGNIEW FAJKLEWICZ studied physics at Jagiellonian University in Cracow, Poland and later applied geophysics at the Mining Academy in Cracow. He received his M.S. (dipl. ing.) degree in geophysics in 1956.

Since 1954 he has worked in the geophysics department of the Mining Academy as an assistant to the professor, has lectured on general geophysics, seminars of instrumentation gravimetry and magnetometry. At the same time since 1956 he has been employed in the Institute of Mining Mechanics at the Polish Science Academy. He is interested in problems connected with geophysical mining.

Fajklewicz is a member of the Polish Geological Society.

ROY W. GOULD was born in Los Angeles, California on April 25, 1927. He received his B.S. degree in electrical engineering at the California Institute of Technology in 1949 and his M.S. degree at Stanford University in 1950. He completed his study for the Ph.D. degree in physics at the California Institute of Technology in 1955.

In 1951 and 1952 he was employed at the Caltech Jet Propulsion Laboratory as a research engineer working on the guidance system of the Corporal missile. During his graduate study in physics he held a National Science Foundation Fellowship and the Howard Hughes Fellowship. Since 1955 he has been on the staff of the Electrical Engineering Department of the California Institute of Technology where he is now Associate Professor. He is teaching and conducting research in the field of physical electronics and is currently concerned with microwave interaction with plasmas. He is also a consultant to the electron tube laboratory of the Hughes Research and Development Laboratory.

Dr. Gould is a member of Tau Beta Pi, Sigma Xi, the Institute of Radio Engineers, and the American Physical Society.

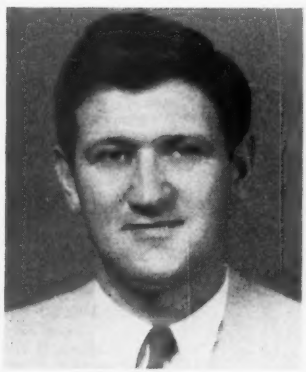
G. E. HIGGINS was educated at the Royal School of Mines, London, where he received his B.Sc. degree in oil technology in 1938, and is an Associate of the Royal School of Mines. From 1938 to 1940 he was engaged in geological and torsion balance surveys in Venezuela with the Caracas Petroleum Corporation. In 1941 he joined the exploration department of Trinidad Leaseholds Limited (now Texaco Trinidad Inc.) and was successively engaged in surface mapping and subsurface investigations. Since 1946 he has served as liaison between the company's geological department and the geophysical contractors with the prime concern of planning surveys and interpreting the seismic and gravity data. He was appointed to senior exploration geologist in July 1954.

He is a member of The American Association of Petroleum Geologists, the Society of Exploration Geophysicists, the Institute of Petroleum, and the Geologists' Association, London.

ROBERT B. MCEUEN received his B.A. and M.A. degrees in geophysics from the University of California (Berkeley) in 1952 and 1954, respectively. From 1954 to 1956 he was employed by the Pan American Petroleum Corporation working both in operations and research. He entered the University of Utah in 1956 where he was awarded his Ph.D. degree in 1959. Since 1958 he has been associated with the Pure Oil Research Center in Crystal Lake, Illinois. He is a member of Society of Exploration Geophysists and the Society of the Sigma Xi.

IRWIN ROMAN has an A.B. degree from Washington University and the M.A. and Ph.D. degrees from The University of Chicago. He was employed by the Geophysical Research Corporation from 1925 to 1930. He has taught at Washington University, Northwestern University, Vanderbilt University, and Michigan College of Mining and Technology. Since 1935, he has been a geophysicist with the U. S. Department of the Interior in the Bureau of Mines or the Geological Survey. Besides publications in geometrical optics, interior ballistics, and exploration geophysics, his contributions include a well-explorer and a magnetic gradiometer.

He is a member of The Sigma Xi, Phi Beta Kappa, American Association for the Advancement of Science, Mathematical Society of America, American Geophysical Union, and Society of Exploration Geophysicists. In the Union, he has served as Vice-President and President of the section of Terrestrial Magnetism and Atmospheric Electricity, and on the Membership and Corporation Membership committees, on the latter as chairman. In the SEG he is serving his second term as an Associate Editor of GEOPHYSICS, and is Chairman of the Subcommittee on Russian Translations.



HAROLD O. SEIGEL was born in Toronto, Canada in 1924. He obtained the degrees of B.A. in 1946 and M.A. in 1947 in applied mathematics (theoretical physics) at the University of Toronto.

In 1949 he was granted the degree of Ph.D. in geophysics at the same institution with a thesis on the development of a method of induced polarization for detection of sulphide mineralization.

From 1949 to 1952 he was assistant to the manager of the geophysical department of Newmont Exploration Limited, Jerome, Arizona. Since December, 1952, he has been engaged in consulting practice in mining geophysics with office in Toronto, Canada.

He is a member of the Canadian Institute of Mining and Metallurgy, the Association of Professional Engineers of the Province of Ontario, of the Geological Association of Canada, of the American Geophysical Union, and of the Society of Exploration Geophysicists.

M. B. WIDESS received the B.S. (1933) and the Ph.D. (1936) degrees in electrical engineering from the California Institute of Technology. He was affiliated with Western Geophysical Company for the subsequent six years and since then has been on the geophysical staff of Pan American Petroleum Corporation, occupied primarily with the development and evaluation of interpretational and field methods in seismic exploration. His present position is Division Geophysical Technical Supervisor in Fort Worth.

Dr. Widess was elected Editor of the Geophysical Society of Tulsa in 1957. He is a member of SEG, EAEG, AAPG, AGU, the Fort Worth Geophysical Society, and the Seismological Society of America.

Biographies of the following authors appear in the earlier issues of GEOPHYSICS: Joseph W. Berg, Jr., v. 22, p. 471; G. J. Blundun, v. 24, p. 409; Kenneth L. Cook, v. 21, p. 212; Leendert de Witte, v. 22, p. 166; Warren G. Hicks, v. 21, p. 883; G. L. Taylor, v. 13, p. 291; R. Vajk, v. 21, p. 887; Stanley H. Ward, v. 18, p. 482

SOCIETY ROUND TABLE

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RICHARD A. GEYER, *Editor*

LOCAL SECTIONS

Ark-La-Tex Geophysical Society (6), Shreveport, La., chartered March 12, 1949, officers elected in May. *Meetings:* Monthly, last Monday, noon luncheon ($1.50), Captain Shreve Hotel.
Virgil Teufel, *pres.*
J. A. Boydstun, *v-pres.*
R. H. Wardell, *secty-treas.*, Western Geophysical Co., 322 Fairfield Bldg., Shreveport, La.

Canadian Society of Exploration Geophysicists (9), Calgary, Alta., chartered January 24, 1952, officers elected in February. *Meetings:* Monthly, no set schedule.
H. J. Kidder, *pres.*
M. B. Dobrin, *v-pres.*
P. J. Savage, *secty-treas.*, Nance Exploration Co., Condon Bldg., Calgary, Alta.

Casper Geophysical Society (11), Casper, Wyoming. Chartered May 23, 1953, officers elected in May. *Meetings:* Monthly, 1st Monday, 7:00 P.M., dinner ($2.75), Townsend Hotel, Casper, Wyoming.
G. L. Ellis, *pres.*
B. A. Tuller, *v-pres.*
Robert Davenport, *secty-treas.*, Wyoming Seismograph Co., Box 631, Casper, Wyoming.

Coastal Bend Geophysical Society (24), Corpus Christi, Texas, chartered May 29, 1959, officers elected in May.
Walter Pfennig, *pres.*
J. W. Bolinger, *v-pres.*
James Vetters, *treas.*
B. C. Johnson, *secty.* Forest Oil Corp., Box 1356, Corpus Christi, Texas.

Cochabamba Geophysical Society (23), Cochabamba, Bolivia, chartered May 4, 1959, officers elected in December.
Paul D. Balbin, *pres.*
Roger Heggblom, *v-pres.*
Frank Ellsworth, *secty-treas.*, Western Geophysical Co., Casilla 1495, Cochabamba, Bolivia.

Dallas Geophysical Society (4), Dallas, Texas, chartered August 7, 1948, officers elected in December. *Meetings:* Monthly, usually 2nd Monday, 8:00 P.M., Fondren Science Bldg., Southern Methodist University.
H. F. Dunlap, *prer.*
E. F. McMullin, *1st v-pres.*
M. S. Hathaway, *2nd v-pres.*
W. B. Heroy, Jr., *secty-treas.*, Geotechnical Corp., Box 28277, Dallas 28, Texas.

Denver Geophysical Society (8), Denver, Colorado, chartered May 19, 1950, officers elected in May. *Meetings:* Monthly, 1st Monday, noon luncheon ($2.35), Petroleum Club.
J. E. Thompson, *pres.*
J. C. Hollister, *v-pres.*
F. L. Travis, *secty-treas.*, Tower Exploration, Inc., 3600 S. Huron St., Englewood, Colorado.

Geophysical Society of Edmonton (23), Edmonton, Alta., Canada, chartered March 20, 1959, officers elected in December.
A. S. Gibson, *pres.*
R. F. Keller, *v-pres.*
R. D. Jacques, *secty-treas.*, Mobil Oil of Canada, Ltd., Financial Bldg., Edmonton, Alta.

Fort Worth Geophysical Society (5), Fort Worth, Texas, chartered August 7, 1948, officers elected in May. *Meetings:* Monthly, 4th Monday, noon luncheon ($1.50), Texas Hotel.
O. A. Strange, *pres.*
P. C. Reed, *v-pres.*
C. H. Thurber, *treas.*
U. A. Rowe, *secty.* Champlin Oil & Refg. Co., Box 9365, Fort Worth, Texas.

Four Corners Geophysical Society (20), Durango, Colo., and Farmington, N. M., chartered June 19, 1958, officers elected in May.
J. P. Badami, *pres.*
F. E. Endacott, Jr., *1st v-pres.*
J. F. Wright, *2nd v-pres.*
G. D. Sindorf, *treas.*
L. E. Schneider, *secty.*, Empire Geophysical, Inc., Box 1484, Durango, Colo.

Geophysical Society of Houston (2), Houston, Texas, chartered February 14, 1948, officers elected in May. *Meetings:* Monthly, noon luncheon.
D. P. Carlton, *pres.*
S. P. Worden, *1st v-pres.*
K. A. Webb, *2nd v-pres.*
S. M. Pena, *treas.*
J. L. Bible, *secty.*, 1045 Esperson Bldg., Houston 2, Texas.

Jackson Geophysical Society (15), Jackson, Miss., chartered May 12, 1955, officers elected in May. *Meetings:* Monthly, during 3rd week, 5:30 P.M., Robert E. Lee Hotel.
R. C. Cole, *pres.*
J. E. MacGregor, *v-pres.*
W. A. McGarry, *secty-treas.*, Pan American Petroleum Corp., Box 689, Jackson, Miss.

Montana Geophysical Society (14), Billings, Mont., chartered April 12, 1954, officers elected in December. *Meetings:* Monthly, 2nd Monday, 7:30 P.M., Billings Petroleum Club.
R. E. Whitmore, *pres.*
W. H. Dawson, *1st v-pres.*
N. L. Hull, *2nd v-pres.*
T. E. Young, *secty-treas.*, Shell Oil Co., Box 2547, Billings, Mont.

New Mexico Geophysical Society (19), Roswell, N. M., chartered September 18, 1957, officers elected in May.
E. J. Medley, *pres.*
R. E. Lawson, *1st v-pres.*
T. E. Daly, *2nd v-pres.*
H. C. Ives, *secty-treas.*, Atlantic Refg. Co., Box 6640, Roswell, N. M.

Geophysical Society of Oklahoma City (10), Okla. City, Okla., chartered September 30, 1952, officers elected in May. *Meetings:* Monthly, 2nd or 3rd Monday.
A. J. Oden, *pres.*
C. L. Howell, *1st v-pres.*
H. J. Fenton, *2nd v-pres.*
W. S. Hart, *treas.*
E. M. Peacock, *secty.*, Sohio Petroleum Co., 1606 N. Broadway, Oklahoma City, Okla.

Pacific Coast Section, SEG (3), Los Angeles and Bakersfield, Calif., chartered April 12, 1948, officers elected in November. *Meetings:* Monthly, 2nd Thursday, noon luncheon ($2.00) Biltmore Hotel, Los Angeles.
R. B. Moran, Jr., *pres.*
W. P. Wilson, *v-pres, N.D.*
J. P. Gates, *v-pres, S.D.*
N. A. Webb, *secty-treas.*, Richfield Oil Corp., 5900 Cherry Ave., Long Beach, Calif.

Permian Basin Geophysical Society (7), Midland, Texas, Chartered January 30, 1950, officers elected in December. *Meetings:* Monthly, 2nd Tuesday, 7:30 P.M., Midland Women's Club.
R. A. Baile, *pres.*
J. E. Clark, *1st v-pres.*
J. W. Rogers, *2nd v-pres.*
R. E. Phipps, *treas.*
D. M. Matson, *secty.*, Midwest Oil Corp., 1500 Wilco Bldg., Midland, Texas.

Regina Geophysical Society (22), Regina, Sask., Canada, Chartered March 20, 1959, officers elected in December.
A. C. Armstrong, *pres.*
D. M. Sawtelle, *v-pres.*
C. E. Dalik, *secty-treas.*, Mobil Oil of Canada, Ltd., 1755 Hamilton St., Regina, Sask., Canada.

Geophysical Society of South Texas (12), San Antonio, Texas, chartered November 9, 1953, officers elected in March. *Meetings:* 1st and 3rd Wednesdays, noon luncheon, Sommers Cafeteria.
W. Harry Mayne, *pres.*
J. W. E. Edmonson, *v-pres.*
P. J. Rudolph, *secty-treas.*, Petty Geophysical Engrg. Co., Drawer 2061, San Antonio 6, Texas.

Southeastern Geophysical Society (13), New Orleans, La., chartered April 1, 1954, officers elected in January. *Meetings:* Monthly, 3rd Monday, noon luncheon ($1.50), St. Charles Hotel.
George Morgan, *pres.*
J. T. McMaster, *1st v-pres.*
D. R. Scheel, *2nd v-pres.*
O. J. Rauschenbach, *secty-treas.*, Continental Oil Co., 414 Carondelet Bldg., New Orleans 12, La.

Southwest Louisiana Geophysical Society (16), Lafayette, La., chartered January 4, 1956, officers elected in December.
Neal Clayton, *pres.*
J. A. Standridge, *1st v-pres.*
C. J. Sieb, *2nd v-pres.*
J. S. Peterson, *treas.*
F. H. Hammons, *secty.*, Pan American Petroleum Corp., Box 1463 OCS, Lafayette, La.

Geophysical Society of Tulsa (1), Tulsa, Oklahoma, chartered February 2, 1948, officers elected in May. *Meetings:* Monthly, 2nd Thursday, 7:00 P.M., meeting only, University of Tulsa, 224 Petroleum Science Hall.
T. S. Green, *pres.*
J. E. Hawkins, *1st v-pres.*
P. H. Garrison, *2nd v-pres.*
R. B. Fisher, *treas.*
B. L. Bass, *secty.*, Texaco, Inc., Box 2420, Tulsa 2, Okla.

Utah Geophysical Society (17), Salt Lake City, Utah, chartered October 29, 1956, officers elected in September.
R. J. Lacy, *pres.*
L. D. Oster, *1st v-pres.*
G. R. Harris, *2nd v-pres.*
J. B. Latimer, *secty-treas.*, Shell Oil Co., 33 Richards St., Salt Lake City Utah.

Asociación Venezolana de Geofísica (21), Caracas, Venezuela, chartered January 5, 1959, officers elected in March.
W. J. Pfeffer, *pres.*
D. F. Warner, *1st v-pres.*
C. W. Penney, *2nd v-pres.*
D. W. Danz, *treas.*
R. L. Garduño, *secty.*, Seismograph Service Corp. of Venezuela, Aptdo 1488, Caracas, Venezuela.

STUDENT SOCIETIES AFFILIATED

Colorado School of Mines Society of Student Geophysicists
Joseph R. Anzman, *secty.* Department of Geophysics, Colorado School of Mines, Golden, Colorado
Meetings: Monthly, 2nd Monday, 4:00 P.M.

Geophysical Society of Saint Louis University
Norman J. Guinzy, *secty.* 410 Vandalia, Collinsville, Illinois
Meetings: Monthly, 2nd Wednesday 7:30 P.M., meeting only, Institute of Technology

SEG Houston Student Section
Reed B. Kubena, *secty.* 1816 Lynnview, Houston 24, Texas
Meetings: to be announced

University of Toronto Geophysical Society
D. W. Strangway, *secty.* 49 St. George Street, Toronto 5, Ontario
Meetings: Bi-weekly, alternate Thursday, 4:00 P.M., 49 St. George Street

University of Tulsa Student Geophysical Society
Fred D. Munzlinger, *secty.* Department of Geophysics, 600 South College, Tulsa, Oklahoma
Meetings: Weekly, Thursday, 4:00 P.M., Petroleum Science Bldg.

Trans-Pecos Student Section
Meetings: to be announced

Pennsylvania State University Geophysical Society
Wm. R. England, *secty.* College of Mineral Industries, University Park, Pa.
Meetings: to be announced

University of Utah Geophysical Society
James D. Morgan, *secty.* College of Mines and Mineral Industries, Salt Lake City 1, Utah
Meetings: Monthly, 1st Thursday Noon, Mines Building. Other special meetings to be announced

A & M College of Texas Student Geophysical Society
Edward C. Hanson III, *secty.* Geology and geophysics dept., A & M College of Texas, College Station, Texas

SOCIETY AFFILIATIONS

American Association for the Advancement of Science

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Petroleum Exploration Society of Libya

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Sam Frazier, *President*

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the name of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

John W. Allingham (J. R. Balsley, H. R. Joesting, J. H. Swartz & R. G. Henderson)
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Rafat Badrawy (R. H. Bixby, G. W. Dennis & W. M. Guirguis)
Wilbur Wright Baldwin (J. C. Pollard, J. J. Pitts, J. B. Meitzen & J. D. Hudson)
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ANNOUNCEMENTS

29TH ANNUAL INTERNATIONAL MEETING PLANNERS

Since last November the chairmen of the committees for the 29th Annual International Meeting have met every month to coordinate their plans. The above picture was taken during one of these meetings. Standing, left to right, are: Joe C. Waterman, Shell Oil Co., arrangements; Dean Walling and Tom Slaven, Western Geophysical Co., entertainment; and Harry H. Sisson, Monterey Oil Co., publications. Seated, left to right, are: Klaas van der Weg, General Petroleum Corp., housing; William Basham, Standard Oil Co. of California, exhibits; Bart W. Sorge, United Geophysical Corp., finance and vice-chairman; Flint H. Agee, United Geophysical Corp., general chairman; Ted H. Braun, The Superior Oil Co., technical program; and Forrest F. Lambrecht, Texaco, Inc., publicity. Committee chairmen absent when the picture was made are: R. L. Stites, Ohio Oil Co., registration; and Mrs. V. E. Prestine, ladies program.

JACKSON GEOPHYSICAL SOCIETY EXPENDS SCHOLARSHIP FUND

The Executive Committee of the Jackson Geophysical Society has transmitted the balance ($250) of its scholarship fund to Prof. H. W. Straley, III, of the School of Ceramic Engineering, Georgia Institute of Technology, to be awarded to Mr. Donald Vough, a Senior in the Geophysics Option who received the stipend last fall, and completed his term this spring.

This is the second year that the Jackson Geophysical Society has made this scholarship award; the previous year's award having been given to Mr. M. L. Fuller.

This brings to a close the geophysical scholarship awards of the Jackson Geophysical Society. No further contributions for scholarship awards have been received, and the scholarship fund is exhausted, according to M. D. Butler, Chairman of the Scholarship Committee." We are discontinuing the awarding of further scholarships, Butler said, and no plans for further soliciting for scholarship funds are being made, principally due to the fact that many of the jamor oil companies are now setting up scholarship programs of their own, as well as those through the SEG Foundation."

NEW EDITORIAL STAFF FOR MATHEMATICAL TABLES AND OTHER AIDS TO COMPUTATION

The Division of Mathematics of the National Academy of Sciences—National Research Council announces that Harry Polachek, Technical Director of the Applied Mathematics Laboratory of the David Taylor Model Basin, has been appointed Chairman of the Editorial Committee for the quarterly journal *Mathematical Tables and Other Aids to Computation* effective January 1959. He succeeds C. B. Tompkins of the University of California at Los Angeles, who held the post since November 1954. The other members of the Editorial Committee are: C. C. Craig, A. Fletcher, E. Isaacson, D. Shanks, C. V. L. Smith, A. H. Taub, C. B. Tompkins and J. W. Wrench, Jr.

BILLINGS GEOLOGICAL SOCIETY FIELD CONFERENCE

The Tenth Annual Field Conference of the Billings Geological Society will be held in the Sweetgrass Arch—Disturbed Belt area of northwestern Montana the second week of August 1959. Registration will be August 12 in Great Falls and a banquet will be held that night. The field conference will begin the morning of August 13 and will cover the geology of the country between Great Falls and Gibson Reservoir. The group will camp out that night at the reservoir. The day of August 14 will be spent studying the geology of the area between Gibson Reservoir and Helena and a banquet will be held in Helena that night. The morning of August 15 will be spent in the country between Helena and Townsend with the conclusion of the conference in the early afternoon near Townsend.

The purpose of the conference is to acquiant more people with the rock strata, mountain-front structure, and the oil and gas possibilities of the area between Great Falls and Townsend. It is hoped that talks at the banquets can be arranged to include local western history as well as geology.

29TH ANNUAL MEETING PLANS PROGRESS

Committees are hard at work preparing for the 29th annual meeting of the Society of Exploration Geophysicists in Los Angeles November 9–12, 1959.

Monthly meetings of the General Chairman with all the committee chairmen are being held to summarize the previous activities and plan the next steps.

Preparation of an outstanding program is well under way under the broad theme "Integrated Exploration," with internationally known speakers being invited to talk on vital subjects. It is believed that the program will contain material of interest to all "explorationists."

Plans for entertainment, ladies program, exhibits, housing and all the other things which go to make up a successful meeting are being developed energetically.

Those attending the 29th Annual International meeting of the Society will find many ways to enjoy themselves outside the serious programs according to Dean Walling, entertainment chairman.

A welcoming cocktail party for the early arrivals will be held at the Biltmore Hotel on Sunday evening Nov. 8th. This will be followed Monday evening by a get-acquainted cocktail party.

On Wednesday the 11th, the formal dinner dance in the Biltmore Bowl will have a Hawaiian theme and feature Hilo Hattie and her troupe of entertainers.

Football fans will have three fine games available. These are: LA RAMS vs SAN FRANCISCO 49'ers Nov. 8th, UCLA vs NORTH CAROLINA STATE Nov. 13th and SOUTHERN CALIFORNIA vs BAYLOR Nov. 14th.

Details of the Hawaiian trip following the meeting have been mailed directly to all members.

MANDREL ACQUIRES TEXAS DIVISION OF CLEVITE CORPORATION

Mandrel Industries, Inc., has entered into an agreement to purchase substantially all of the assets of the Texas Division of the Clevite Corporation it was announced by George Quist, President of Mandrel Industries, Inc.

Clevite Corporation manufactures a complete line of seismic exploration instruments in its Texas Division, formerly known as the Texas Division of Brush Electronics Company—a Clevite subsidiary.

Mandrel will merge the facilities thus acquired with its Electro-Technical Labs Division, 5134 Glenmont Drive, Houston, Texas, under the direction of D. D. MIZE, vice president and general manager of Mandrel's Houston operations.

PERSONAL ITEMS

Two major Houston geophysical companies were merged May 6 when Robert H. Ray Co. announced the purchase of all stock in McCollum Exploration Company.

A new firm, known as Robert H. Ray Company, Inc., will operate McCollum's Geograph, a weight dropping seismic instrument, in the United States, Canada and Australia.

Another company formed last November, McCollum Ray International, Inc., will continue to operate the Geograph (also known as the "Thumper") in all other locations throughout the world.

Holdings assumed by the new owners include the McCollum buildings in Houston; the Midland, Texas, regional processing office plus seven domestic Geograph crews.

BURTON MCCOLLUM, inventor of the Geograph and an Honorary Member of SEG, has established separate facilities in Houston to continue his research in weight dropping and related explora-lems. His new offices are located at 3415 Mercer.

STANLEY H. WARD was Associate Professor of Mineral Exploration in the University of California at Berkeley during the past semester.

California Research Corporation announces the appointment of Dr. LEE P. STEPHENSON to the position of Research Associate in Geophysics at the La Habra Laboratory.

Dr. Stephenson received the A.B. degree in chemistry from Fresno State College in 1947 and the M.S. and Ph.D. degrees in physics from the University of Illinois in 1949 and 1953. His work on the application of a Schlieren microscope technique to certain problems in electrochemistry attracted favorable attention.

Since joining the staff of the La Habra Laboratory in 1953, Dr. Stephenson has worked mostly in the field of experimental seismology.

His contributions have been largely in the basic conceptual design of advanced new methods for the analysis, display and interpretation of reproducible seismic records.

Texas Instruments Incorporated has formed a GeoSciences and Instrumentation division and elected FRED J. AGNICH as a TI vice president to head the new division, President PATRICK E. HAGGERTY announced.

NEWLY ELECTED OFFICERS OF THE PERMIAN BASIN GEOPHYSICAL SOCIETY

From left to right: Don D. Matson, Secretary; John E. Clark, 1st Vice President; Richard A. Baile, President; John M. Armstrong, 2nd Vice President; and Rollin E. Phipps, Treasurer.

1959 OFFICERS FOR THE SOUTHWEST LOUISIANA GEOPHYSICAL SOCIETY, LAFAYETTE, LOUISIANA

From left to right on the front row: Frans H. Hammons, Secretary, Pan American Petroleum Corp.; James S. Petersen, Treasurer, Sinclair Oil & Gas Co.

Back row left to right: C. J. Seib, 2nd Vice President, Marine Exploration Co.; Neal Clayton, President, Sohio Petroleum Co.; John A. Standridge, 1st. Vice President, Phillips Petroleum Co.

Republic Natural Gas Company announces the addition of Mr. A. L. LINEHAN to the geophysical staff. Graduated in 1951 from the University of Texas with a B.S. degree in geology, Mr. Linehan became associated with Geophysical Service Inc., where his work as geophysicist carried him into The Rocky Mountain and Texas Mid-Continent areas, and later into Australia and finally South America. Mr. and Mrs. Linehan, and one daughter are making their home in Dallas. During 1942–46 Mr. Linehan served with the United States Marines where he was commissioned Captain.

J. F. FREEL, President of Research Explorations, Inc., 5134 Westheimer, Houston, Texas, announced today the opening of headquarters offices for Research Explorations (Alaska), Inc. in Anchorage. Freel named ERNEST A. PRATT, former Geophysical Sales Manager for Southwestern Industrial Electronics Company, Houston, as General Manager.

M. R. HEWITT, district geophysicist with Pan American Petroleum Corporation, has been transferred from Edmonton, Canada to Midland, Texas, according to Wm. J. Nolte of Fort Worth, North Texas-New Mexico division exploration superintendent.

Mr. Hewitt will direct the firm's geophysical program in the southern Permian Basin area. He succeeds J. L. MATAYA, who has moved to Calgary, Canada.

CALENDAR OF MEETINGS

1959

September
12 International Oceanographic Congress, New York, New York

October
4– 7 Society of Petroleum Engineers of AIME, Fall Meeting, Dallas
28–30 American Association of Petroleum Geologists, Mid-Continent Regional Meeting, Broadview Hotel, Wichita, Kansas

November
9–12 Society of Exploration Geophysicists, 29th Annual International Meeting, Biltmore Hotel, Los Angeles (Flint H. Agee, General Chairman, United Geophysical Corporation, 1200 South Marengo Avenue, Pasadena 15, California)

1960
April
25–28 American Association of Petroleum Geologists—Society of Economic Paleontologists and Mineralogists, Annual Meeting, Atlantic City, New Jersey

November
7–10 Society of Exploration Geophysicists, 30th Annual International Meeting, Moody Convention Center, Galveston (Walter B. Lee, Jr., General Chairman, Gulf Oil Corporation, Drawer 2100, Houston 1, Texas)

1961
November
5– 9 Society of Exploration Geophysicists, 31st Annual International Meeting, Denver

1962
September
17–20 Society of Exploration Geophysicists, 32nd Annual International Meeting, Calgary, Alberta

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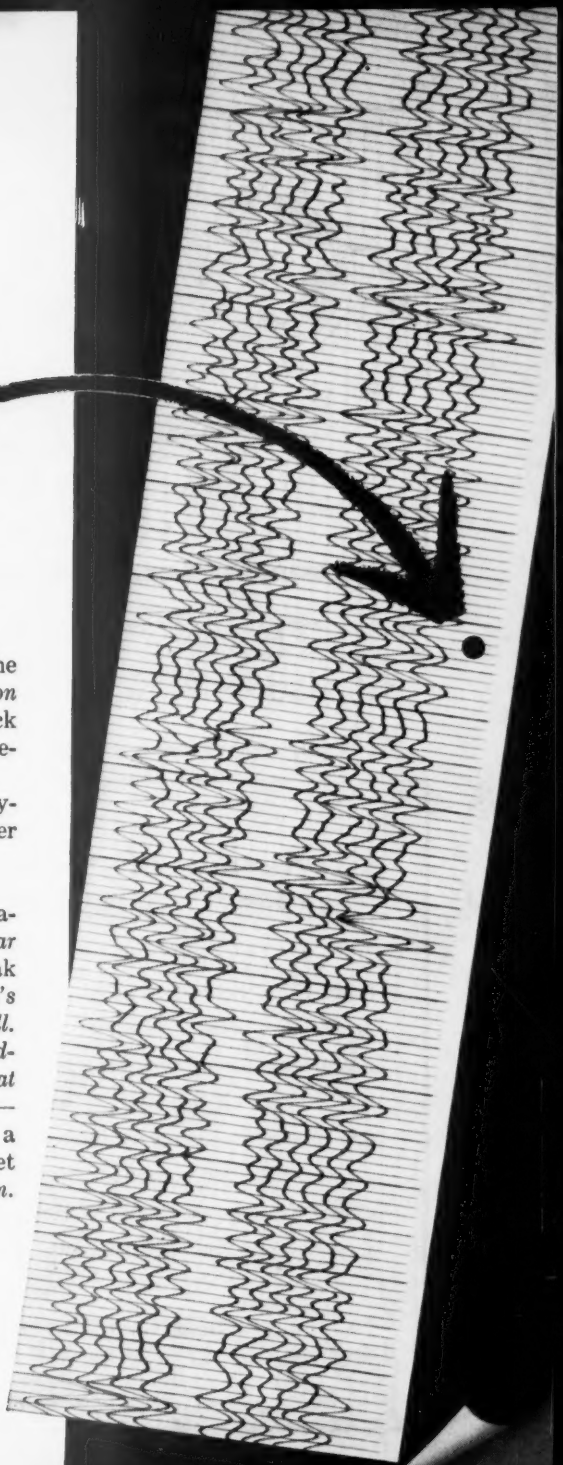

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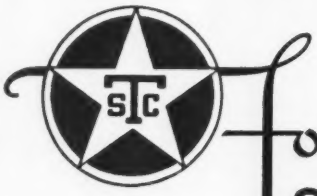

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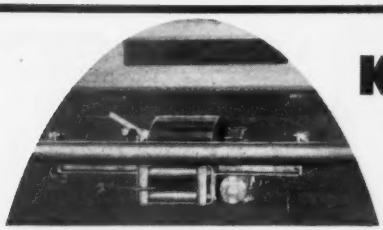

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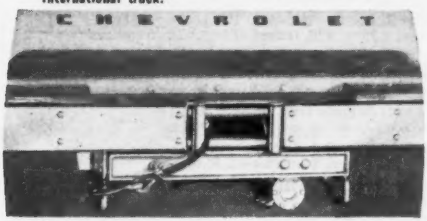

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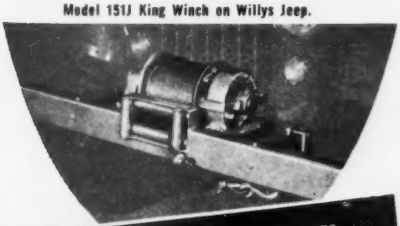

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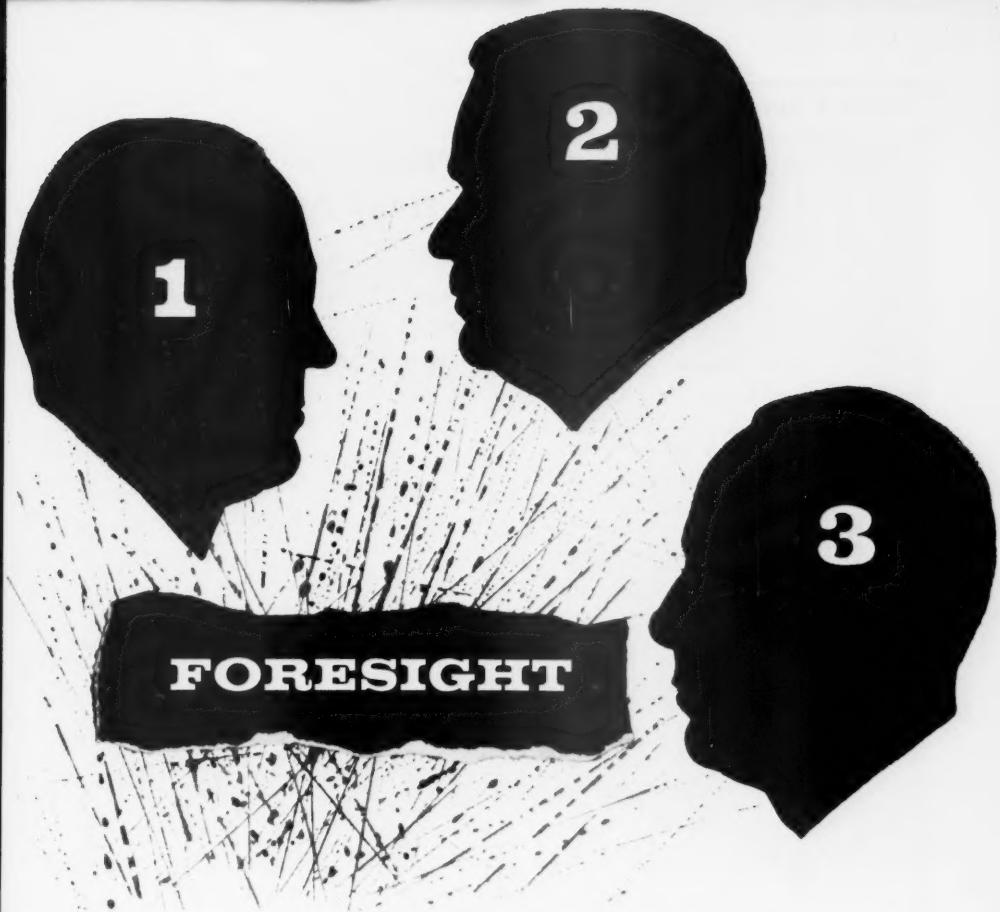

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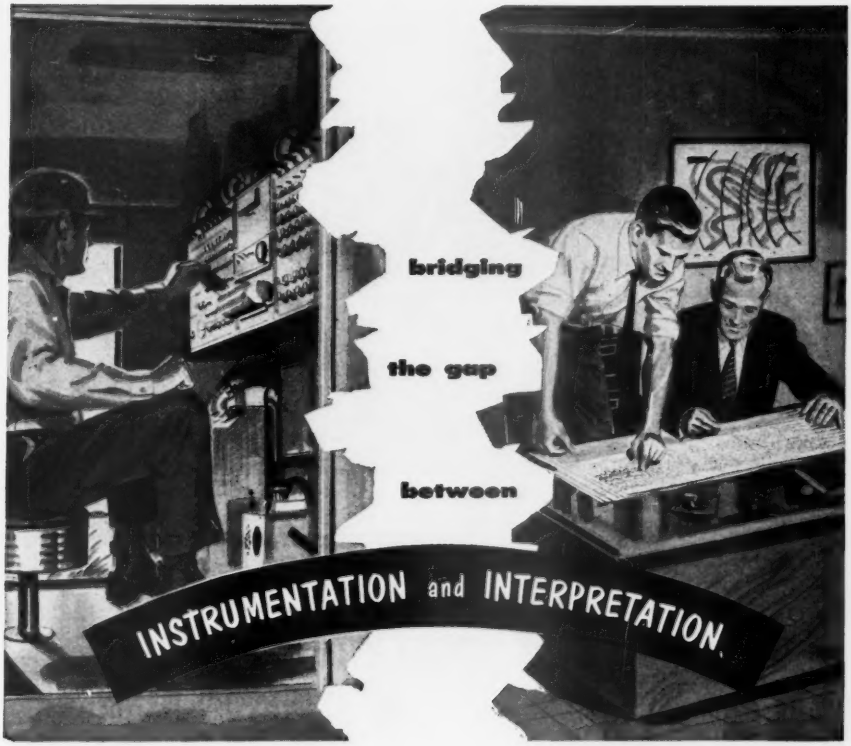

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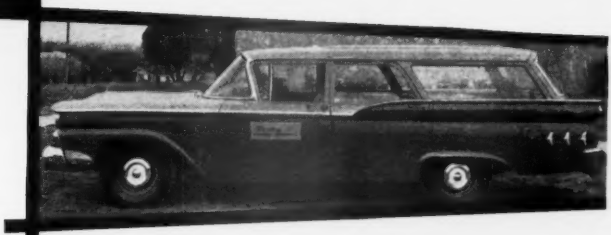

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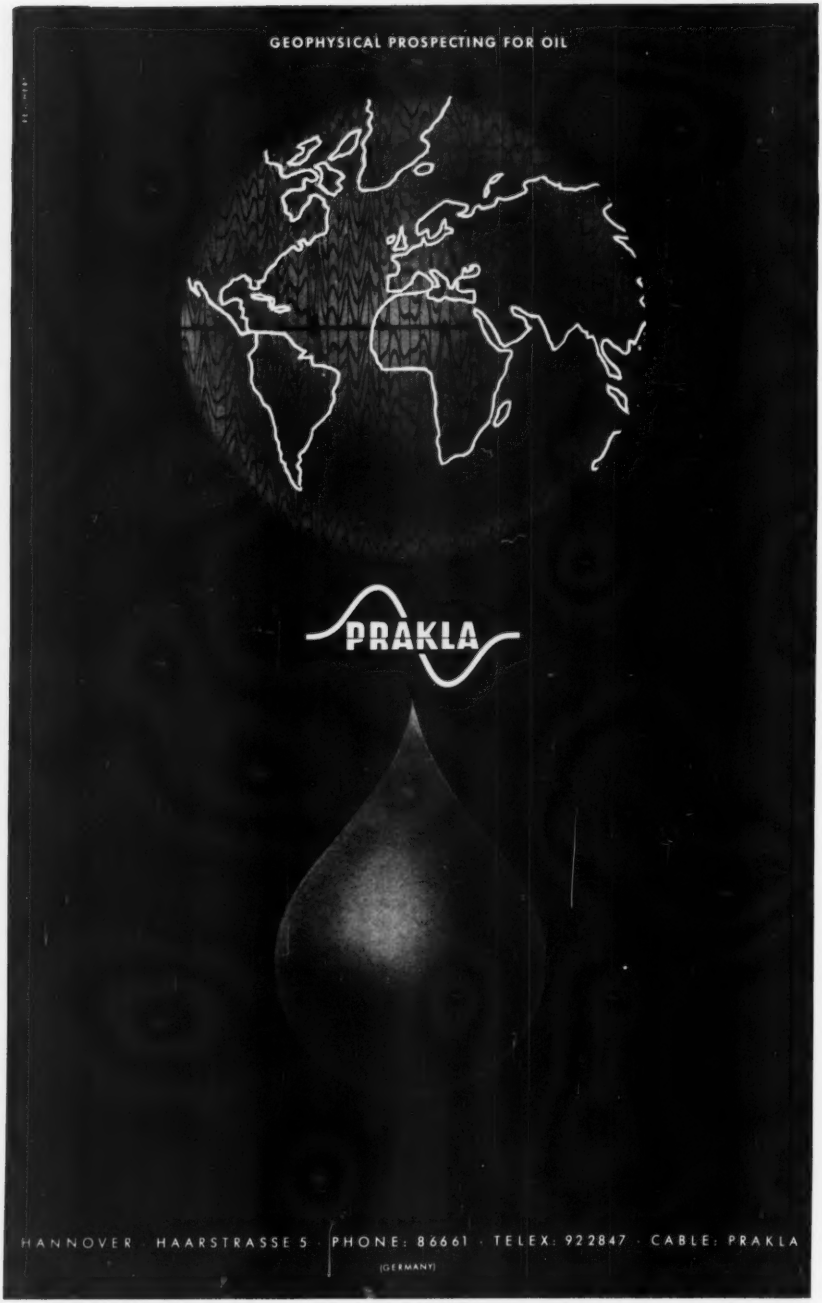
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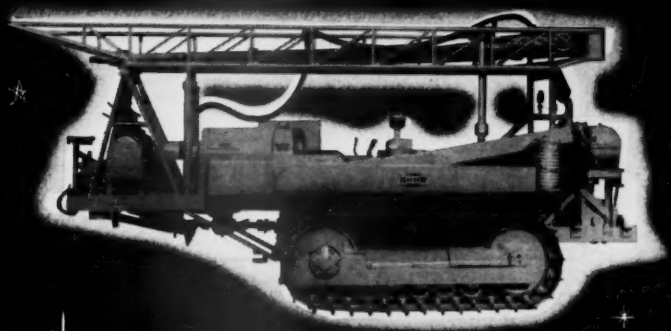

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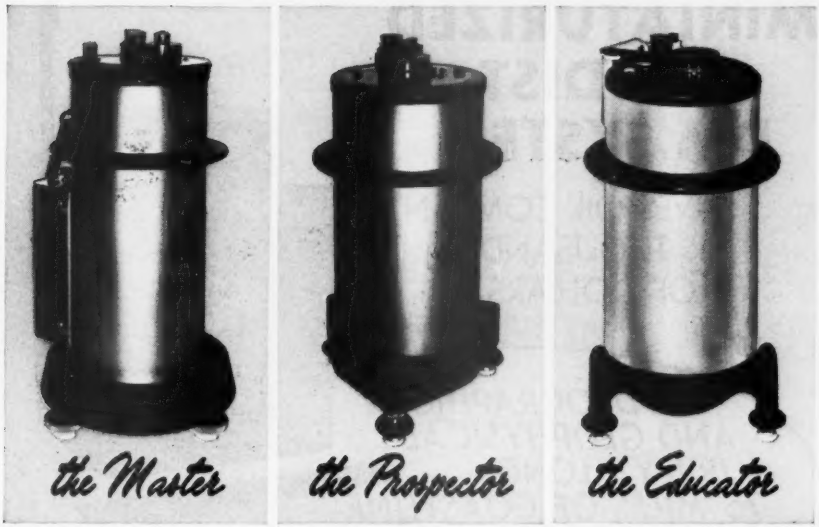

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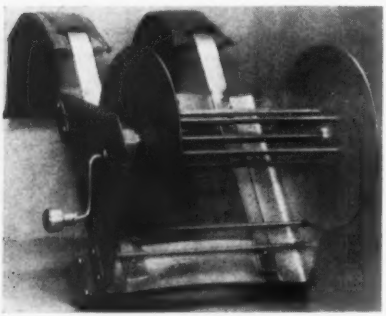

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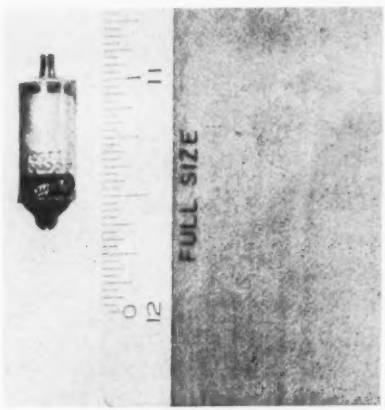

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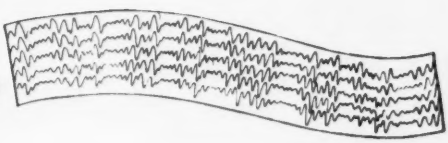

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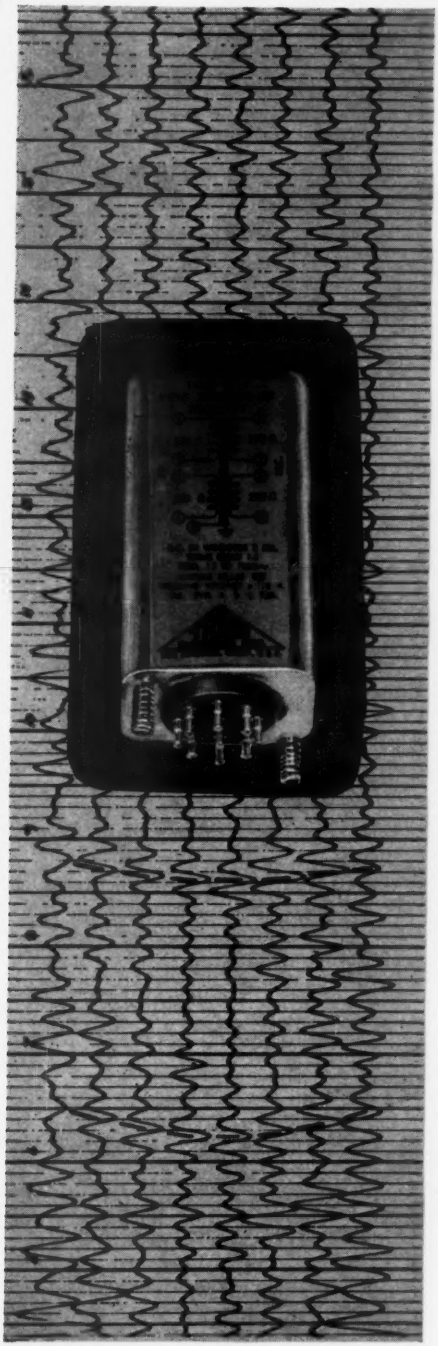

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(Continued from page 54)

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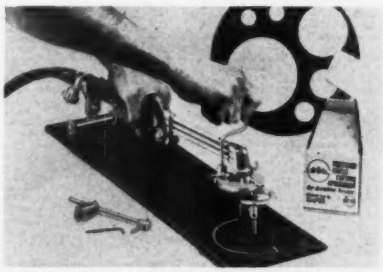
Ross-Martin Company, Tulsa, Oklahoma manufacturer of specialized steel filing cabinets for the oil industry, announces a new five-drawer cabinet to hold electric well logs. By means of two separate follow blocks in each drawer, the five drawer will accommodate 2,500 average electric logs. Ball bearing rollers and strong suspension arms allow drawers to slide all the way out for complete accessibility. This new E-25 electric well long cabinet occupies only 3½ square feet of floor space. Available in either gray or olive green. Custom designed filing supplies, golders, file envelopes and guides for the E-25 are available from stock. **Ross-Martin Company, P.O. Box 800, Tulsa 1, Oklahoma.**

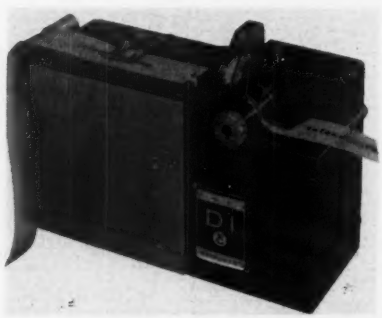
HOLE CUTTING TOOL

A new patented tool, costing about one-tenth that of large complicated machines, is being manufactured for cutting precision holes and various shapes in thick metal plate. Developed for use by the U.S. Navy, the tool attaches to any acetylene cutting torch for such applications as cutting holes through metal walls and decks for pipe and electrical conduit. Squares, rectangles, and odd-shaped holes and solid figures can also be accurately formed for welding fabrication. Because of the tool's small size, it will operate in confined spaces, heretofore usually performed by laborious and expensive free-hand cutting. Marketed under the trade name, OR-O-CO, this new universal tool is priced less than $40. **Ideas, Inc., 214 Ivinson Avenue, Laramie, Wyoming.**



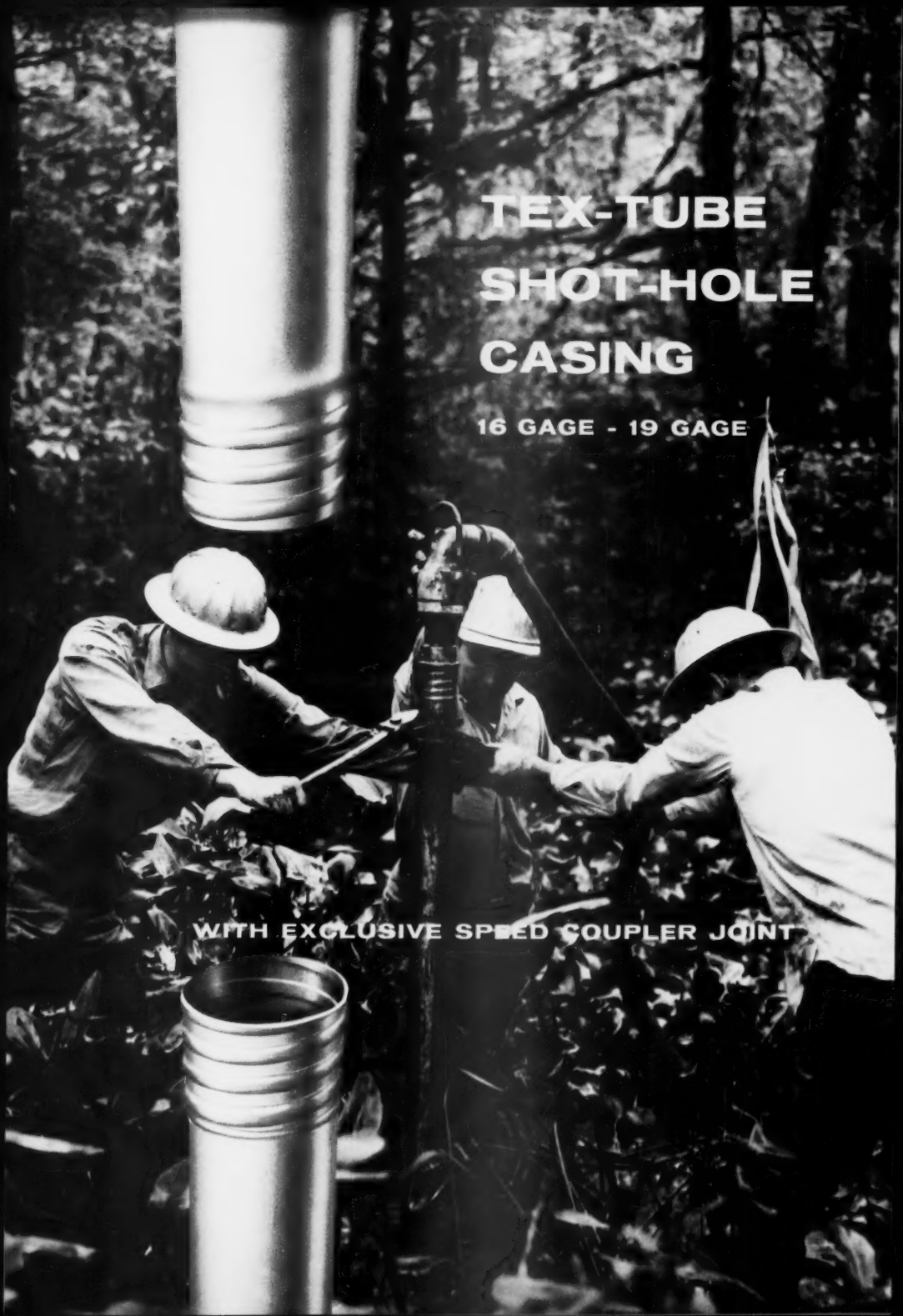
HIGH-SPEED TAPE PERFORATOR

North Hollywood, California, April 22, 1959—A new, moderately priced, high-speed tape perforator with a punching speed of forty columns per second has been announced here today by the Data Instruments Division of Telecomputing Corporation, 12838 Saticoy Street.



The compact unit has a simplified drive mechanism which requires only one eccentric and one cam-generated motion. This reduction in moving parts produces high punching speed and long life. The perforator is sturdily built and features easy access for maintenance. Sealed ball bearings minimize lubrication and carbide

(Continued on page 64)


TEX-TUBE
SHOT-HOLE
CASING
16 GAGE - 19 GAGE
WITH EXCLUSIVE SPEED COUPLER JOINT

TEX-TUBE SHOT-HOLE CASING

Best in the field!

LIGHTWEIGHT

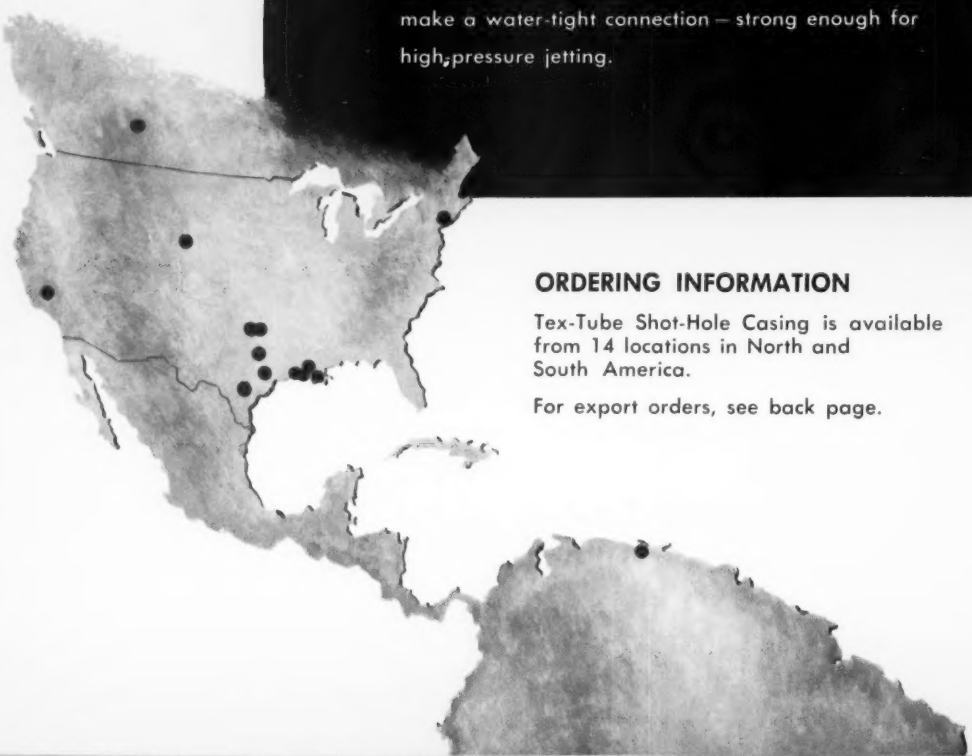
Can easily be carried by one man.

STRONG

Field tests prove strength enough to drill with.

Tex-Tube Shot-Hole Casing is a uniform, quality product, manufactured from high-grade steel in Tex-Tube's Houston mill.

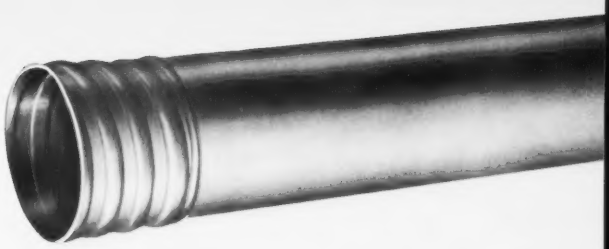
The exclusive Tex-Tube Speed Coupler Joint makes up fast — without collars. Only two quick turns make a water-tight connection — strong enough for high-pressure jetting.



ORDERING INFORMATION

Tex-Tube Shot-Hole Casing is available from 14 locations in North and South America.

For export orders, see back page.



Available in two gages—standard 10-ft. lengths.

16 gage joint—weight 20 lbs.

19 gage joint—weight 13 lbs.

A. Tex-Tube Shot Hole Casing is a must in drilling operations such as this.

B. Tapered joint means easy stabbing. Speed Coupling with only 1½ threads per inch, means fast make up.

C. Typical hand jetting operation in the swamps of Louisiana.

TEX-TUBE, INC. HOUSTON, TEXAS

BATON ROUGE, LOUISIANA • HOUMA, LOUISIANA

Bakersfield, California	Par-Tain Exploration Co.	FAirview 5-3764
Baton Rouge, Louisiana	Tex-Tube, Inc.	ELgin 5-1430
Beeville, Texas	H & T Sales Co.	FLeetwood 8-1642
Dallas, Texas	Engineering Supply Co.	FLeetwood 7-2861
Houma, Louisiana	Bilderback Dynamite Co.	UPtown 2-0861
Houma, Louisiana	Tex-Tube, Inc.	UPtown 2-0569
Houston, Texas	Tex-Tube, Inc.	UNderwood 9-3411
Lafayette, Louisiana	Bilderback Dynamite Co.	CEnter 4-6184
Mills, Wyoming	Teton Tool Co.	CAsper 2-7181
Oklahoma City, Oklahoma	Deupree Distributing Co.	JAckson 8-6740
Oklahoma City, Oklahoma	Grove Hardware Co.	JAckson 8-4886
FOREIGN: Calgary, Alberta, Canada	Seismic Service Supply, Ltd.	5-5691
Caracas, Venezuela	Venezuelan Supply, C. A.	71-53-21
EXPORT: New York City	National Supply Co. Export Division	CIrcle 6-3232

TEX-TUBE
SHOT-HOLE CASING
EXPORT
PACK

- EASY TO LIGHTER
- EASY TO HANDLE
- EASY TO USE IN THE FIELD

ex-tube 4-Pack shot-hole casing being loaded aboard ship at the Port of Houston for direct shipment to location.

Ten Lengths
one package
Each 4-Pack breaks up into four packages of ten joints each.

This handy new package holds ten joints of Tex-Tube shot-hole casing. Four such packages make up into the handy 4-Pack — 40 lengths — for easy shipment. The threaded ends are securely packed in heavy, paraffin-coated, corrugated packing to resist damage to the ends. Thread sections are coated to resist corrosion. The Tex-Tube 4-Pack is bound with steel bands and weighs only 800 lbs. It can be trucked, loaded, and unloaded easily, without damage. Handling costs are reduced all along the line.

In the field, each 4-Pack can be divided into four separate, steel bound packages of ten lengths each. (In this way only the number of lengths to be used needs to be unpackaged.) The rest stay in perfect condition, not underfoot, not liable to be damaged or lost.

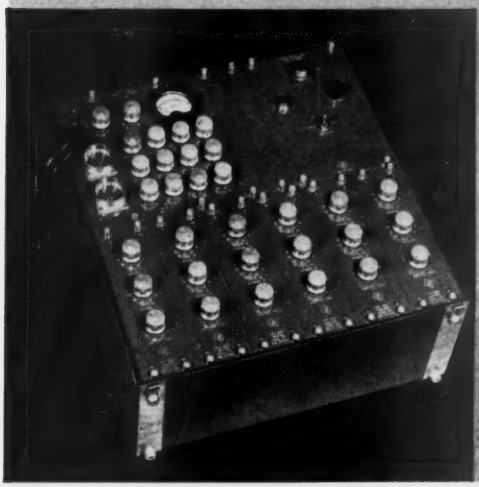
Each package of ten lengths weighs only 130 lbs. in 19 gage and only 200 lbs. in 16 gage. Operations go more smoothly, and the risk of damage and loss is reduced.

TEX-TUBE, INC.

1303 North Post Oak Road,
Houston, Texas

Here are the best two reasons for the REFRACTION REVIVAL!

TI **VLF** VERY LOW FREQUENCY SEISMOGRAPH AND **S-36** HIGH-OUTPUT 2-CYCLE SEISMOMETER



Although the Refraction Seismograph was used as an exploration tool many years before the Reflection method, it was virtually abandoned during the thirties because of the inability of existing equipment to record low frequencies and build up a satisfactory signal-to-noise ratio.

SAVE UP TO 50% ON DYNAMITE— SHOOT ANY TIME OF THE DAY!

Now, the thoroughly field-proved *VLF* Refraction System provides highly usable results for large area surveys or in areas unworkable by the reflection method. Excellent first breaks and second arrivals have been recorded while using less than half the dynamite required by other systems. Furthermore, the *VLF*'s high signal-to-noise ratio permits shooting during the usually windy mid-day hours when other systems cannot produce usable results. With frequency response down to one cycle on the amplifiers and to two cycles on the S-36 seismometers, the versatile *VLF* system is equally satisfactory for the most difficult petroleum exploration programs, mining surveys, and civil engineering projects.

You can be sure of the best attainable refraction results with the compact and portable 12-channel *VLF* system. Write for complete information — specify Bulletin S-308.

TEXAS INSTRUMENTS
INCORPORATED
INDUSTRIAL INSTRUMENTATION DIVISION
3609 BUFFALO SPEEDWAY • HOUSTON, TEXAS • CABLE: HOULAB

a Seismatron system

183

(Continued from page 58)

inserts are used at critical wear points.

The perforator features four-way staggered positioning of the large, rugged punching electro-magnets to provide compactness and maximum force. Rapid response to punching signals is obtained by an overlap. As the drive shaft completes 180 degrees of the complete revolution required to puch each column, the perforator will accept the signal from the next column to be punched.

Safety features include an interlock to prevent the feed from advancing tape until a column has been punched. A visual alarm indicates low tape supply, and audible alarms are available. The unit has anti-bounce latches for smoother, more accurate punching, and an odd-even parity check circuit will spot errors in punching.

Standard models are available from shelf stock. They will accept any standard tape size up to one inch in width, and any code column to 8 channels. Tape width may be changed easily in the field. Special models capable of punching up to 30 channels are available upon request. Units come with desk top or panel (relay rack) mountings. **L. G. McClenning, 12838 Saticoy Street, North Hollywood, California.**

BOOKLET DISCUSSES DRILLING CLAYS

A new concept in drilling muds is advanced in a technical bulletin recently published by the Minerals & Chemicals Corporation of America. The booklet presents the case for Attapulgus Clay as a component for oil well drilling muds in contaminated fresh water as well as salt water systems.

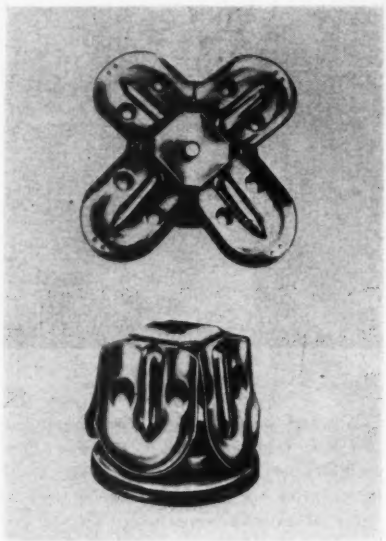
The information presented in the bulletin is the result of several years intensive research into the characteristics of drilling muds. The booklet is profusely illustrated with charts and graphs comparing the various characteristics of attapulgite and other commonly used clays. The figures show yields in fresh water, salt, and gyp systems. Studies into the stability of various type drilling muds in contaminated systems and under high temperature conditions are described and the results are shown graphically. Comparisons are also made of water loss properties between Attapulgus Drilling Clay and other mud systems.

The twelve-page, two-color bulletin discusses in detail the application of Attapulgus Drilling Clay in fresh water, salt water, gyp, oil emulsion and completion mud systems. It presents the relative economics of using Attapulgus Drilling Clay in fresh water systems as well as in contaminated systems.

Known as Technical Information No. 552, the bulletin is available without cost from the **Minerals & Chemicals Corporation of America, Menlo Park, N.J.**

EXPANDING EARTH ANCHORS

The Grip-Tite Company, Winterset, Iowa have announced a greatly enlarged line of Grip-Tite expanding earth anchors. The new line is all steel, four way, with asphalt coating.



Exclusive features include: Grip-Tite wing dimples, and deeply embossed base plates, which distribute stress evenly and resulting in more holding power; four-way design that places a greater portion of expanding area into undisturbed earth and which also results in more holding power in average soils, the addition of nut retainers which prevents the anchors from sliding up the rod during installation and which also permits salvage of rods in the event of line abandonment or relocation; and exclusive double-strength anchor top which prevents damage from the expanding tool during installation.

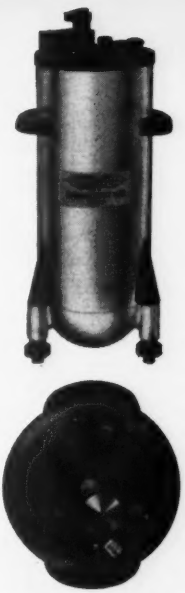
The Grip-Tite Company state that the new line guarantees low initial cost, low installation cost and ease of installation.

(Continued on page 74)

Exploration crews the world over are using more World-Wide Gravity Meters than ever before — for good reasons! Weighing only eight pounds, this economical, *built-to-take-it*, portable meter operates anywhere in the world in all kinds of weather with maximum accuracy. World-Wide's easy-to-read meter is thoroughly temperature compensated, requires *no thermostats, no barometric temperature corrections.* Sealed in a vacuum, the World-Wide Gravity Meter gives dependable, trouble-free service in the most difficult prospect areas.

Exclusive Features Of The World-Wide Gravity Meter:

- Easy reading counter . . . operator reads the meter without removing from the tripod.
- Recessed level bubble . . . eliminates level bubble creep.
- World-wide range on all meters . . . regardless of latitude.
- Approximately 100 milligal range on counter . . . minimizes resetting instrument in rugged terrain.



World-Wide Gravity Meters are available on purchase or rental/purchase plans. Each instrument carries a full-two-year warranty. Write or wire for complete details.

WORLD-WIDE INSTRUMENTS, INC.

3802 South Shepherd, Houston, Texas • Cable Address: GRAVIMETER HOUSTON

Low Cost Seismic Sections the following morning with...

VIP*

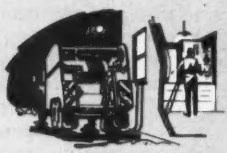
VARIABLE INTENSITY PLOTTER

VIP's speed, low initial cost and lowest processing cost per profile, make it ideally suited for day-to-day processing of seismic data in the field office. It is easily transported from prospect to prospect, and, of most importance, *VIP* is compatible and operative with all makes of amplifier and magnetic transducer systems.

This first ALL-ELECTRONIC system devised for variable density presentations rapidly corrects for time or depth and compresses wide areas of seismic data into section form. The *VIP* cross section closely approaches a geologic section and is easily comprehended.

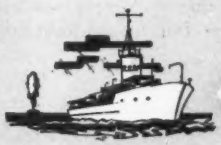
Operating directly from any magnetic record, the *VIP* processes 24 channels at one time (or sequentially) over full record length — corrections may be viewed as applied — maintains timing accuracy of ± one millisecond. For complete information on the field-proved *VIP*, write for Bulletin No. S-322.

Use Versatile VIP everywhere . . .



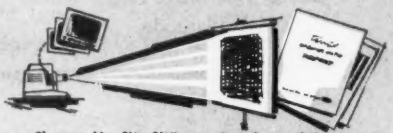
Use with recording equipment at night for field processing.

Van or trailer-mounted VIP can serve several parties.



Use aboard ship for high production marine surveys.

Every Central Processing Office should have a VIP for quick, economical cross sections.



Photographic 2¼ x 3¼" negatives have obvious mailing and storage advantages . . . may be slide-projected, or blown up to report size or working size sections.

TEXAS INSTRUMENTS
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a Seismatron system

*Trademark of Texas Instruments Incorporated

SEISMOGRAPH SURVEYS*

*long and short term contracts

C. N. PAGE A. E. "SANDY" McKAY C. J. LOMAX

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For FAST SERVICE on all your recording supplies

CALL SIE

TAPES

RECORDING CHARTS

PHOTOGRAPHIC SUPPLIES

A complete stock of quality-controlled, individually-inspected SIE magnetic recording tapes; *fresh* photographic paper and film; guaranteed precision-ruled charts — these supplies are maintained by SIE ready for immediate shipment as soon as your order is received.

Equally important are the top-quality results assured when you specify SIE recording supplies. For example: SIE magnetic recording tapes are required to be *noise free*, and are inspected to make certain they meet performance specifications with SIE instruments.

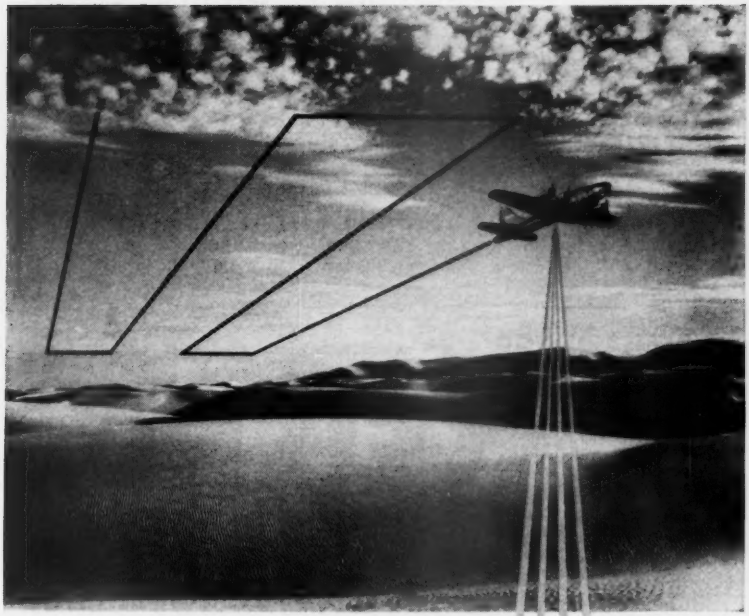
Call Eddie Nix at HOmestead 5-3471 in Houston (days), or MOhawk 4-3765 (nights) for immediate shipment. Overseas, cable SIECO, Houston. You'll be certain of unmatched service and quality.

SIE

SOUTHWESTERN INDUSTRIAL ELECTRONICS COMPANY

A Division of Dresser Industries, Inc.

10201 Westheimer • P. O. Box 13058 • Houston 19, Texas



FAIRCHILD first with RADAN® 500

Doppler radar navigational system for aerial geodetic and survey purposes!

Only RADAN 500 combines the proven features of military-type Doppler systems with the latest advances in the state of the art.

This newest Fairchild navigational aid is the most modern Doppler radar equipment available. With it precision flight paths can be flown over any terrain without photos, maps, or ground stations of any kind. Since much of the cost of surveying lies in obtaining photography or establishing ground stations for accurate flight path control, the RADAN 500 dramatically reduces survey costs. Actual flying can get underway faster and surveys are completed sooner.

This new Fairchild service is available for geophysical and photomapping projects anywhere in the world. For complete information write or TWX:

WHAT IS DOPPLER?

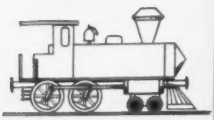
The RADAN 500 Doppler radar automatically and continuously determines ground speed and drift angle of the aircraft. From this information an electronic "brain" in the aircraft computes its exact position, enabling the pilot to fly precise flight paths over desert, jungle, ice or any featureless terrain without ground control of any kind.

FAIRCHILD AERIAL SURVEYS, INC., Los Angeles, Calif.: 224 East 11th Street Offices in: New York • Chicago • Boston • Birmingham • Houston Brussels • Istanbul • Vancouver, B.C. • Toronto • Guatemala City • Caracas • Bogota • Lima • La Paz • Rio de Janeiro • Buenos Aires • Santiago

100 Years ago

Beginning of Oil Production

40 Years ago



Mintrops Patent
of Seismic Refraction Method

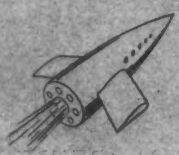
38 Years ago

SEISMOS
G. M. B. H.
Hanover-Germany
established by Ludger Mintrop

30 Years ago

first Measurement with
transportable Gravity Meter by
SEISMOS

3 Years ago



first seismic Fieldwork
with Transistor Amplifiers by
SEISMOS

FORTUNE ELECTRONICS' DC-2

. . . the economical record-playback unit for office and field use

Fortune Electronics' new dynamic correction record-playback unit makes it possible for you to obtain accurate, corrected playbacks in the office or on location with a minimum initial investment. *The compact DC-2 handles any shot spread configuration. Spread length adjustments are calibrated directly in feet.* The unit accommodates standard six and one-half or seven inch tapes. Weighing only 82 pounds, the DC-2 is easy to handle—requires minimum space.

SPECIFICATIONS

Physical Characteristics	
Maximum Dynamic Correction	150 ms
Static Correction	±50 ms
Drive	400 cycle Hysteresis Motor Gear Coupled to Drum
Size	15 x 18 x 14 inches
Weight	82 pounds
No. of Traces	26 or 28
Electrical Characteristics	
Power Requirements	8 amperes @ 12 volts
Signal/Noise Ratio	50 db RMS to RMS
Timing Accuracy	±1 ms
Total Harmonic Distortion	2½% @ 100% Record Level
Crossfeed	—37 db @ 10 cycles

For complete details on the all new DC-2 write or call:

Fortune Electronics, Inc.

H. H. HAPPEL—H. H. HAPPEL, JR.

2505 SOUTH BOULEVARD, HOUSTON, TEXAS

Represented in Dallas, Texas and Tulsa, Oklahoma by Indel Supply Company

LET Milligal
GO TO BAT
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Whether you make a home run or strike out may be determined by your batting experience. You are assured of accurate and dependable interpretations when you use

GRAVITY SURVEYS

They are based on the proper application of the latest scientific methods.

Call, wire or write for prompt, accurate geophysical surveys.

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WE WEIGH THE EARTH

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to find it out...

Compagnie Générale de Géophysique

50 rue Fabert Paris 7e

(Continued from page 64)

They also guarantee the fastest delivery in the industry.

Grip-Tite in addition to expanding earth anchors, manufacture Drilling Mast and Derrick Guy Wire anchors, floor block and service truck anchors, rock anchors, pipe line anchor assemblies and oil field anchors.

RADIOTELEPHONE

Pictured above is the first dual channel KAAR TR247. The second channel addition was a special modification for a police agency in the Union of South Africa.

Normally one of the five units in KAAR ENGINEERING CORP.'s package of field communications, the TR247 is one of the rare "suitcase" units with data transmission capabilities. The 50 watt unit normally finds application at a field camp base station in exploration work. **KAAR Engineering Corp., 2995 Middlefield Rd., Palo Alto, Calif.**

REDUCE DROPOUT ERRORS

Methods of reducing signal dropouts in magnetic tape are discussed in "Sound Talk" Bulletin No. 37 available on request from Minnesota Mining and Manufacturing Company, Dept. E9-200, 900 Bush Avenue, St. Paul 6, Minn.

The four-page bulletin, titled "Reduction of Dropout Errors in Magnetic Recording Systems," is illustrated with photomicrographs of common types of coated-in tape flaws, photographs showing the effect of small dust specks on recorded data tracks, a cutaway view of 3M's new precision reel, a photograph of a modern tape coating machine, and diagrams pertaining to the dropout problem.

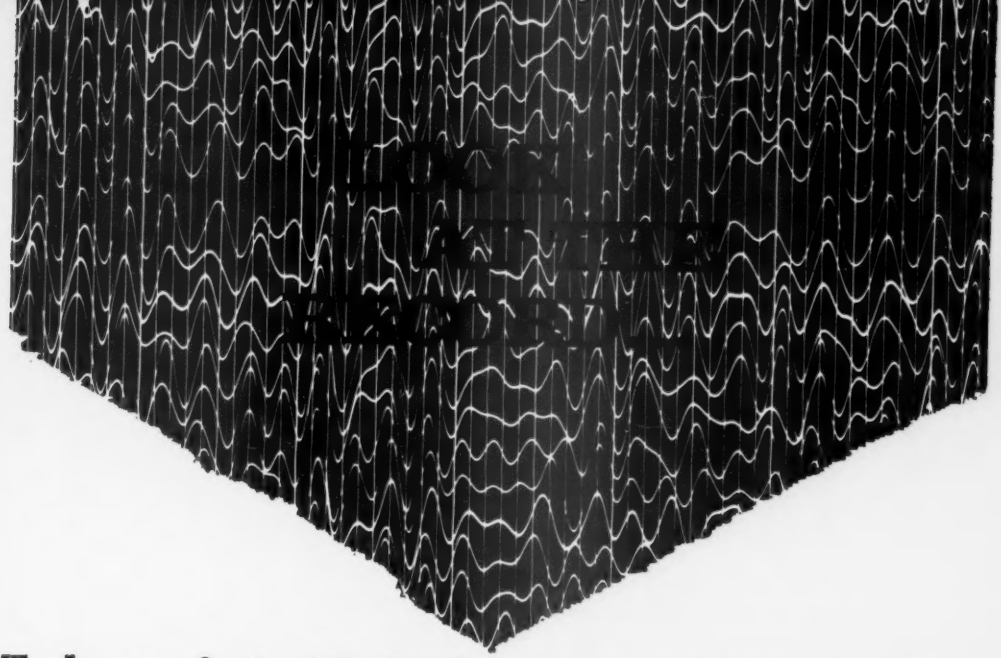
A great reduction in tape flaw has resulted since the 3M Company engineered improvements in coating methods in 1957. Despite this, the bulletin notes, smaller dropouts continue to be of significance in highly critical applications. Dents in the backing caused by foreign particles or creases caused by handling also result in dropouts. The bulletin points out the value of 3M's new precision reel as an aid in solving such handling problems. **Minnesota Mining and Manufacturing Company, 900 Bush Avenue, St. Paul 6, Minnesota.**

PROTECTIVE HAND LOTION

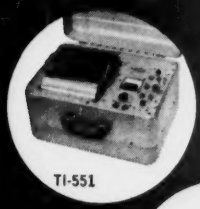
A new protective product is now available for the first time by **VANFAIRE CO., North Hollywood, California,** for the industrial worker with hands exposed to

chemicals, oils, grease, solvents, plastics, and paint. VANFAIRE provides a new invisible protection against resulting rashes. Applied like any hand lotion, it is soluble in soap and water and protects the hands up to 12 hours. After many tests it is now being used widely by the plastic, aircraft, electronics, and chemical industries on the West Coast.

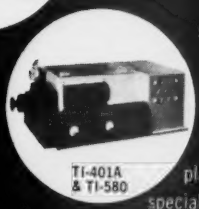
(Continued on page 90)



Techno... first with the future in magnetic recording



TI-551



TI-401A & TI-580

First to make seismic magnetic recording instruments commercially available... first to use the direct process which set a standard in the industry... first with simultaneous dynamic corrections! Serial No. 1 still is in use... still is compatible with Techno's newest instruments. Today, Techno is first again with a fully-transistorized portable system in a single package. In the field or playback center Techno sets the trend in specialized magnetic recording instruments... first with the future! Techno Instrument Company / 6666 Lexington Ave. / Los Angeles 38, Calif. / phone toll free Enterprise 3304

THE GEOPHYSICAL SOCIETY OF TULSA

announces VOLUME 5 of

THE PROCEEDINGS OF THE GEOPHYSICAL SOCIETY OF TULSA

This issue contains the following papers:

How Thin is a Thin Bed? by M. B. Widess

Seismic Exploration in the Appalachian Region by Leland Snow

Topography and Its Apparent Effect on Average Velocity by H. M. Thralls

Correlation of Adjacent Gravimeter Surveys by V. L. Jones

The Seismod Record Section by A. C. Reid

Featured in this issue is a nearly complete section of abstracts of technical papers presented before seventeen Local Sections of SEG during the 1957-58 season.

BACK ISSUES AVAILABLE

Volume 4. Tenth Anniversary Number

This issue contains nine original papers on various phases of exploration geophysics.

Volume 3. Density Data

This issue presents density data, in tabular and graphic form, of core fragments and cuttings from wells in several geological basins. Emphasis is placed on West Texas basins.

Volume 2. Co-operation of Geology and Geophysics

Case histories of geological and geophysical co-operation successful in petroleum exploration are presented in this issue.

Volume 1. Joseph A. Sharpe Memorial

The text of this first volume is concerned with magnetic susceptibility of rocks, its determination and usefulness, magnetic susceptibility measurement on rocks in the Llano uplift, on well cores from pre-Simpson Paleozoic rocks, and from wells in West Texas and Southeast New Mexico.

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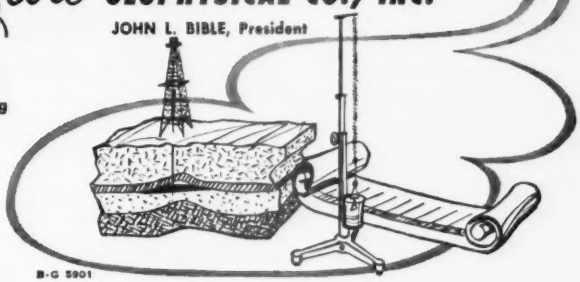

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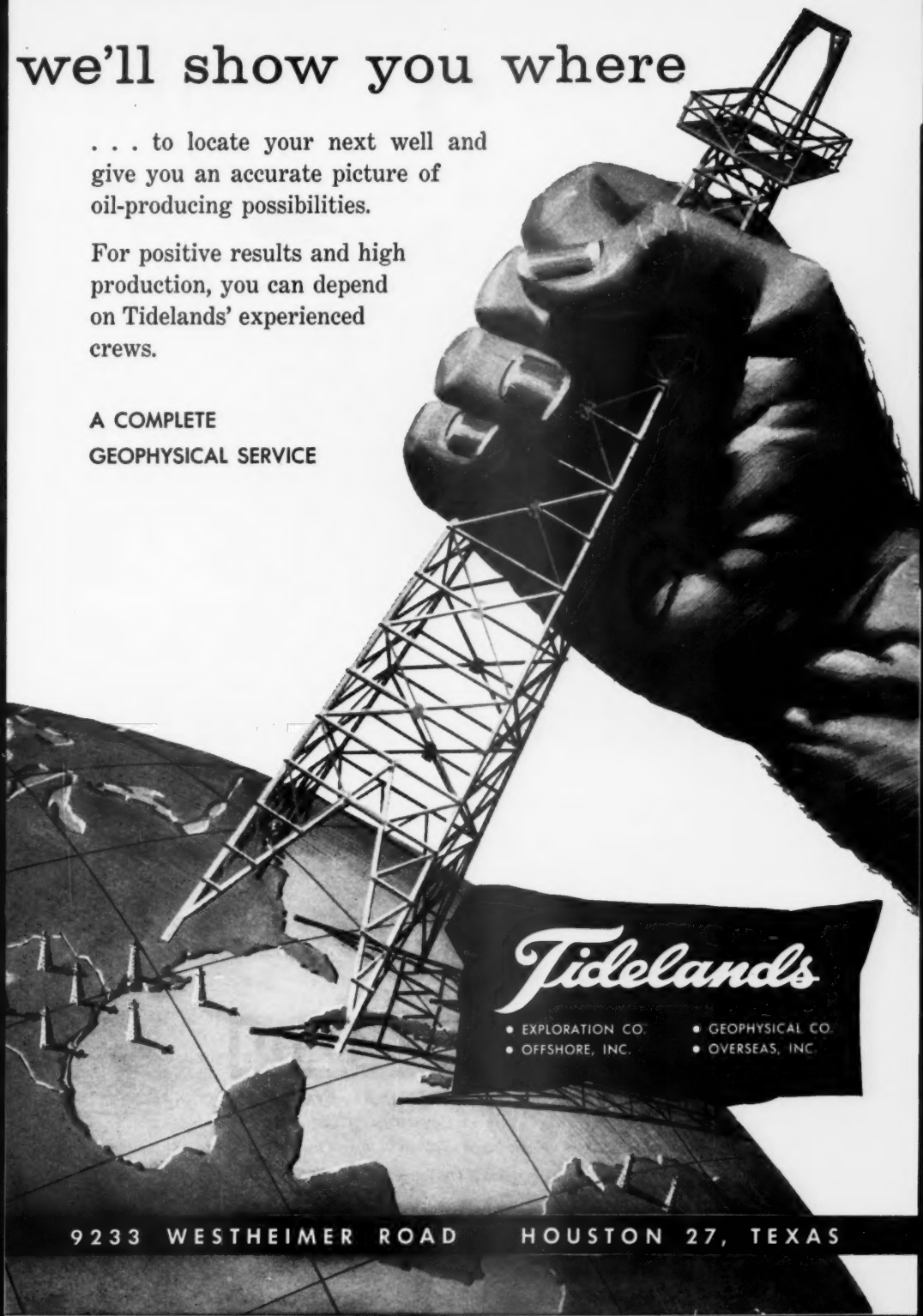

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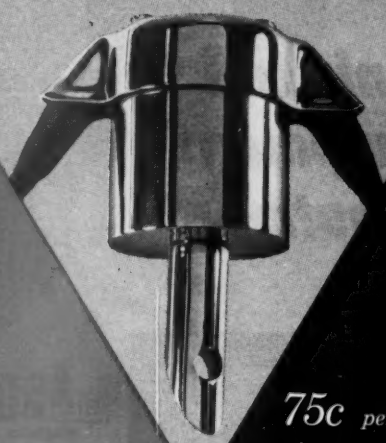

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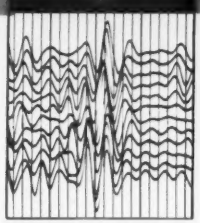

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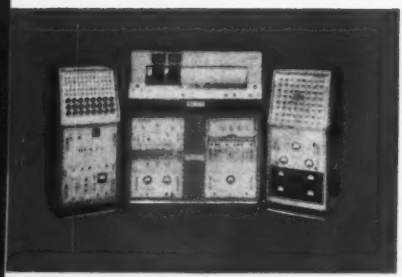

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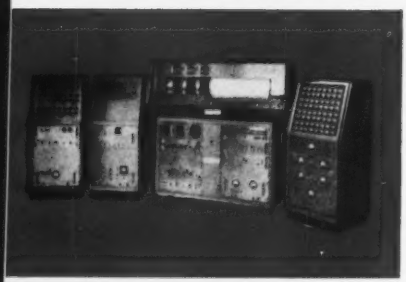

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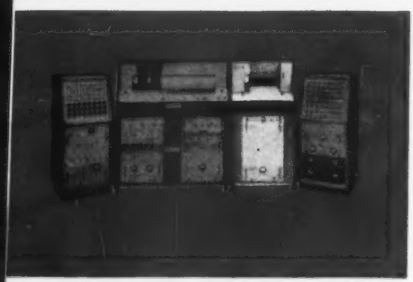

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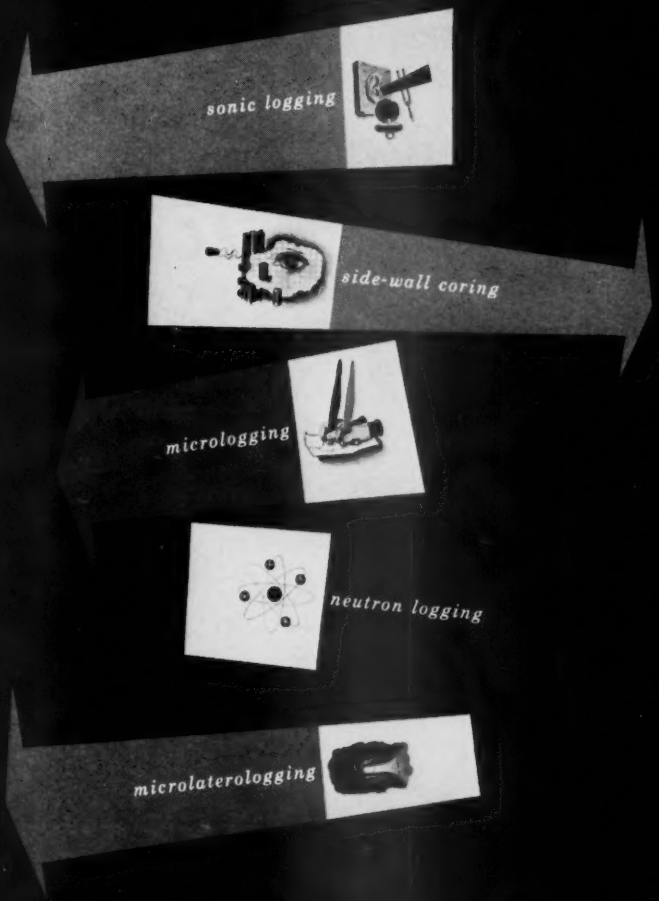

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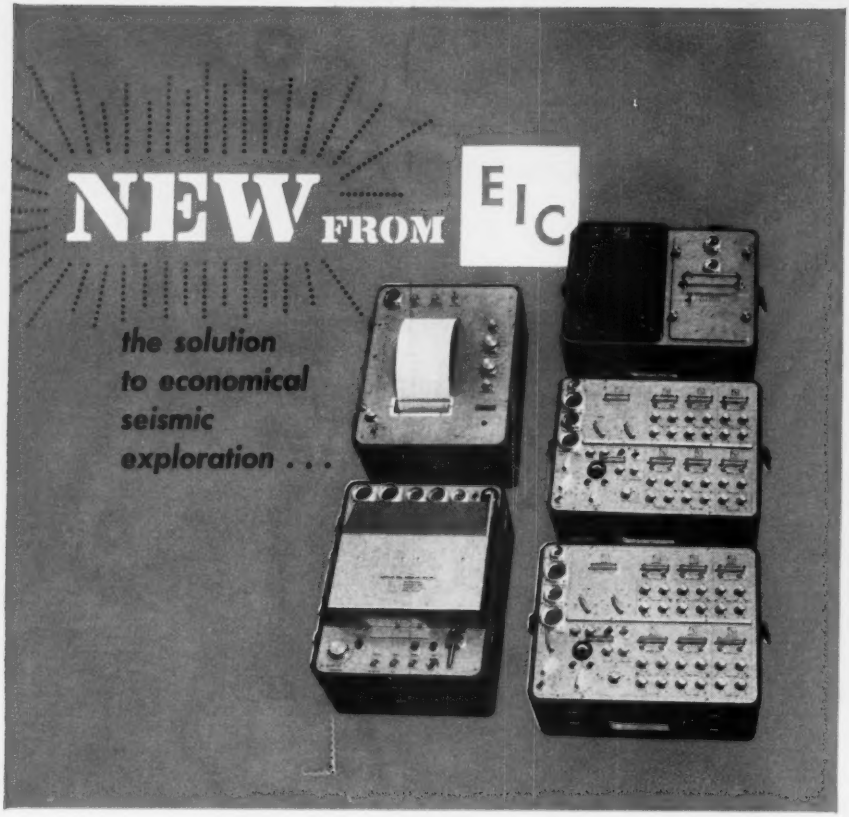

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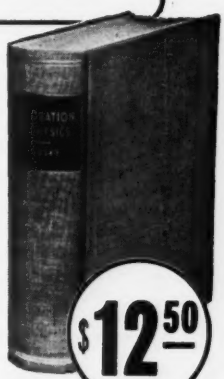

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(Continued from page 74)

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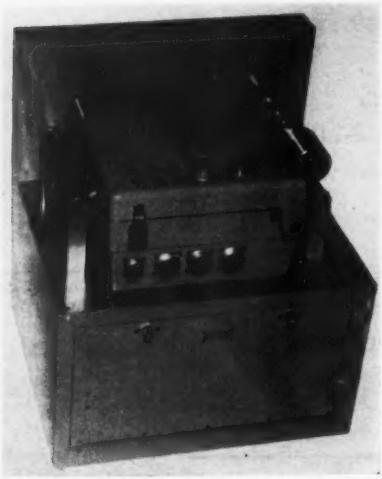

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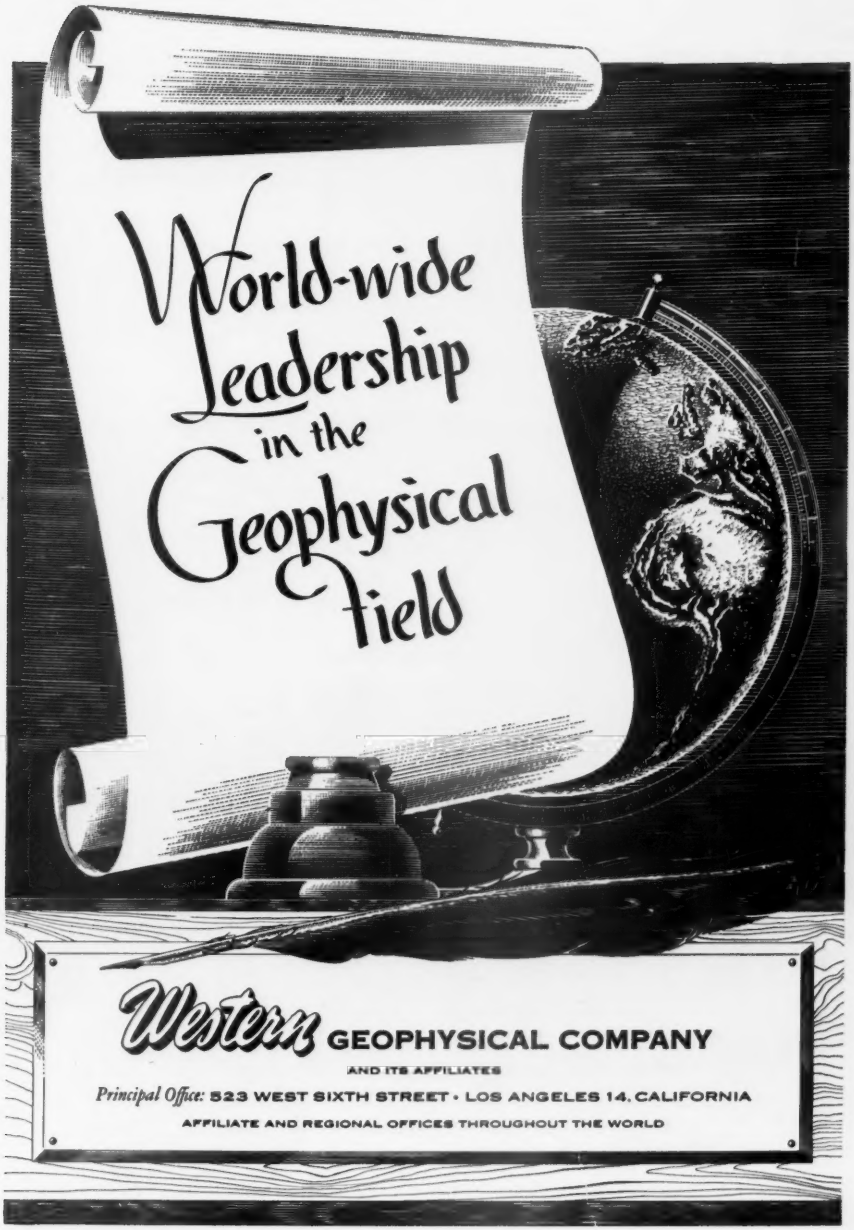
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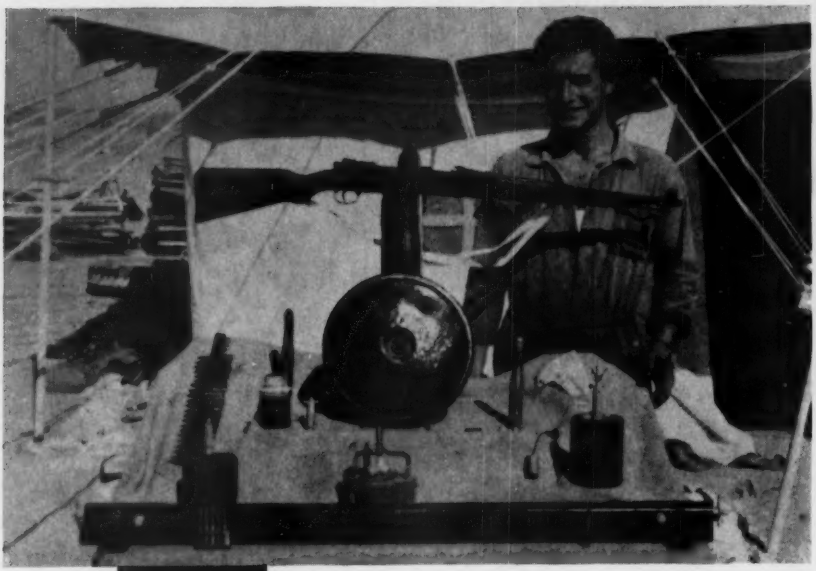

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